Arnold Schwarzenegger
Governor

INDOOR-OUTDOOR AIR LEAKAGE OF APARTMENTS AND COMMERCIAL BUILDINGS

PIER FINAL PROJECT REPORT

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Prepared By:

Lawrence Berkeley National Laboratory
Dr. Ashok Gadgil, Principal Investigator
Dr. Phillip N. Price, Scientist
Arman Shehabi, Graduate Research Assistant
Rengie Chan, Graduate Research Assistant
Berkeley, California 94720
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Prepared For:

Public Interest Energy Research (PIER) Program
California Energy Commission

Gina Barkalow
Project Manager

Beth Chambers
Contract Manager

Kelly Birkinshaw
Program Area Lead
Energy-Related Environmental Research

Laurie ten Hope
Office Manager
Energy Systems Research

Martha Krebs
Deputy Director
ENERGY RESEARCH & DEVELOPMENT DIVISION

B.B. Blevins
Executive Director

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Preface

The Public Interest Energy Research (PIER) Program supports public interest energy research and development that will help improve the quality of life in California by bringing environmentally safe, affordable, and reliable energy services and products to the marketplace.

The PIER Program, managed by the California Energy Commission (Energy Commission), conducts public interest research, development, and demonstration (RD&D) projects to benefit California.

The PIER program strives to conduct the most promising public interest energy research by partnering with RD&D entities, including individuals, businesses, utilities, and public or private research institutions.

PIER funding efforts are focused on the following RD&D program areas:

- Buildings End-Use Energy Efficiency
- Energy Innovations Small Grants
- Energy-Related Environmental Research
- Energy Systems Integration
- Environmentally Preferred Advanced Generation
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- Renewable Energy Technologies
- Transportation

Indoor-Outdoor Air Leakage of Apartments and Commercial Buildings is the final report for the Improved Prediction of Indoor Exposure to Outdoor Air Pollution in Apartment and Commercial Buildings project (contract number 500-02-004, work authorization number MR-035), conducted by the Indoor Environment Department of Lawrence Berkeley National Laboratory. The information from this project contributes to PIER's Energy-Related Environmental Research Program.

For more information about the PIER Program, please visit the Energy Commission's website at www.energy.ca.gov/pier/ or contact the Energy Commission at 916-654-5164.

Table of Contents

List of Figures

List of Tables

Abstract

This project compiled and analyzed available data concerning indoor-outdoor air leakage rates and building leakiness parameters for commercial buildings and apartments. The project team reviewed the literature to determine the current state of knowledge of the statistical distribution of air exchange rates and related parameters for California buildings, and to identify significant gaps in the current knowledge and data. Very few data were found from California buildings, so the team compiled data from other states and some other countries. Even when data from other developed countries were included, data were sparse and few conclusive statements were possible. Commercial buildings and apartments seem to be about twice as leaky as single-family houses, per unit of building envelope area. Little systematic variation in building leakage with construction type, building activity type, height, size, or location within the U.S. was observed. Although further work collecting and analyzing leakage data would be useful, a more important issue may be the transport of pollutants between units in apartments and mixed-use buildings, an under-studied phenomenon that may expose occupants to high levels of pollutants such as tobacco smoke or dry cleaning fumes.

Keywords: Air exchange, air leakage, airtightness of buildings, apartment buildings, building envelope, building shell, commercial buildings, indoor air quality, infiltration

Executive Summary

Indoor-outdoor air exchange rates affect energy costs because conditioned (heated or cooled) air that exits a building must be replaced by air from the outdoors. This air must then be brought to the indoor temperature through use of air conditioning or heating. Excess air exchange leads to unnecessary energy costs and a waste of resources.

However, insufficient air exchange is also undesirable. Air exchange removes pollutants that were generated indoors and admits pollutants that were generated outdoors, so the air exchange rate is a key parameter in controlling indoor air quality. Most pollutant concentrations are much higher indoors than outdoors, so insufficient air exchange leads to inadequate indoor air quality and thus discomfort and detrimental health effects.

Indoor-outdoor air exchange takes place in two ways: through intentional ventilation (i.e., through an open window or via the heating, ventilating, and air conditioning system) and through undesired infiltration or "leakage." Air leakage from single-family homes has been shown to result in significant household energy losses that increase the cost of heating or cooling a house by 50% or more (Sherman and Matson 1996). However, little has been documented about air exchange rates from multi-unit residential buildings (apartments) and nonresidential buildings. Likely, many of these buildings have unnecessarily high (and thus costly) air exchange rates, but some may have air exchange rates that are too low and may even be acutely dangerous by allowing buildup of carbon monoxide and other toxics. Moreover, a better understanding of the air exchange rates for apartments and nonresidential buildings is necessary for authorities to determine proper "shelter in place" guidelines in the event of a toxic chemical release, whether by industrial accident or terrorist attack. Without knowing the statistical distribution of air exchange rates, public health officials can only guess how long indoor air will remain safer than outdoor air in the event of a disaster.

This report discusses what is known about leakage into (and out of) apartment buildings and nonresidential buildings. Nonresidential buildings will be referred to as "commercial buildings," even though some are schools or used for other non-commercial activities.

Much of the analysis concerns the *leakage parameter,* which quantifies the amount of outdoor air that enters a building when there is a given pressure difference between indoors and outdoors. This is essentially a measure of the airtightness or leakiness of a building's shell. In contrast, a measurement of a building's *air exchange rate,* which is the rate at which air is entering the building at a particular time, depends not just on properties of the building but also on factors such as the wind speed and direction, operation of the mechanical ventilation system (if any), and the indoor-outdoor temperature difference. This project considers both air exchange rate data and leakiness data, but the emphasis is on the leakage parameter.

The project team reviewed the published literature to determine the current state of knowledge about air infiltration in commercial buildings and multifamily-residential buildings. Previous work in these areas has generally considered either small subsets of the available building data, or simple, univariate summary statistics describing larger data sets. For apartment data these approaches are probably the best that can be done, due to the paucity of data, but for commercial buildings the available data, though sparse, allow more detailed analysis, which this project undertook.

In contrast to the situation for single-family homes (Chan et al. 2005), where there is an available database of more than 70,000 measurements, published data concerning leakage measurements for apartments and commercial buildings are very sparse. The project found data for only 78 multi-unit residential buildings in North America, and for 267 commercial buildings in North America and Europe, including unpublished data from 75 commercial buildings. Only a few buildings are from California, and it is unknown whether there is a large difference in leakiness between buildings in California and buildings elsewhere.

Due to (1) sparseness of data and (2) the fact that buildings were not chosen to be statistically representative of typical buildings, the available data allow only very crude estimates of the statistical distribution of air exchange rates or building leakage area parameters, and of the relationship between leakage parameters and factors such as building size, construction materials, etc. They are, nevertheless, the best available source of information about these relationships and parameters. Given the limitations of the data, all results should be considered provisional.

Analysis of the commercial buildings data suggests that:

1. Within a given category of building activity (education, retail, etc.) there appears to be little systematic variation in leakage parameter as a function of construction type.
2. Within a given construction type (metal-frame, masonry, etc.) there is some evidence that schools and public assembly buildings tend to be somewhat tighter than average and that warehouses tend to be leakier than average.
3. For a given building activity and construction type, buildings with small "footprints" (i.e., small roof area) under 1000 m^2 tend to be 25% to 50% leakier, per unit envelope area, than buildings with large footprints.
4. For a given building activity and construction type, taller buildings appear to be slightly tighter than shorter buildings (with single-story buildings being perhaps 10% to 25% leakier than taller buildings, per unit envelope area). However, the scarcity of tall buildings in the database provides little statistical power to address this issue, and almost all of the tall buildings are office buildings, so a height effect cannot be distinguished from an effect of building type (item 2).
5. For a given building activity, construction type, footprint size, and height, leakiness per unit envelope area is approximately lognormally distributed, with a geometric standard deviation (GSD) between about 1.7 and 2.2. (A "lognormal" distribution means that the logarithms of the data are distributed according to a Gaussian, or "normal," distribution.)
6. On average, commercial buildings may be about twice as leaky as single-family houses, per unit of building envelope area (Chan et al. 2005).

Apartment building data are even more deficient than commercial building data, so no detailed analysis was possible. From the available data, indoor-outdoor air exchange rates and building leakage area per unit of building envelope area seem to be about twice as high (i.e., twice as leaky) for apartments as for single-family homes. This suggests that there may be a potential for substantial energy savings by reducing air infiltration rates for apartment buildings. However, reducing the infiltration rate of outdoor air without reducing the transport of pollutants such as cigarette smoke within the building may further increase the exposure of occupants to pollutants produced elsewhere in the building. The issue of internal transport of pollutants within apartment buildings and mixed-use buildings merits more attention than it has received.

1.0 Introduction

Indoor-outdoor air exchange rates affect energy costs because conditioned (heated or cooled) air that leaves a building must be replaced by air from the outdoors. This air must then be brought to the indoor temperature through use of air conditioning or heating. Excess air exchange leads to unnecessary energy costs and a waste of resources.

Additionally, air exchange removes pollutants that were generated indoors and admits pollutants that were generated outdoors, so the air exchange rate is a key parameter in controlling indoor air quality. Most pollutant concentrations are much higher indoors than outdoors, so insufficient air exchange leads inadequate indoor air quality and thus discomfort and detrimental health effects.

Excessive air exchange wastes energy, costs money, and generates pollution through unnecessary energy generation. Insufficient air exchange can lead to an uncomfortable and unhealthy indoor environment, thereby endangering public health. Knowledge of the statistical distribution of air exchange rates can help determine whether government policy should mandate or encourage certain construction or ventilation practices, or whether additional research is needed before making such a determination.

Although concerns about energy and air pollution are the main motivations behind air infiltration research, knowledge of air infiltration rates is also necessary for assessing risks from intentional or unintentional chemical (or biological) exposures such as industrial accidents, "conventional" air pollution, or terrorist releases of toxic material. If people are told to "shelter in place" (close doors and windows, shut off ventilation) and remain indoors during an industrial accident, how much lower will indoor concentrations be than outdoors? The answer for a given house, apartment, or business depends on its air exchange rate, and the distribution of risk across the population depends on the statistical distribution of air exchange rates. This distribution is fairly well known for single-family homes, as a function of building age and other factors (Chan et al. 2005), but there is little information about apartments or commercial buildings—or "mixed use" residential/commercial buildings, which many cities are promoting as part of a "smart growth" development strategy.

The air infiltration–related properties of a building are referred to as the "airtightness" or "leakiness" of the building, a standard terminology (AIC 1981). This report will discuss the *air exchange rate* (which is a function of building-related parameters and also weather conditions) and the indoor-outdoor *air flow rate at a specified pressure drop* across the building envelope (which is a property of the building alone). Although leakier buildings generally experience higher air flow rates than "tighter" buildings, the air flow rate, like the air exchange rate, depends not just on the building's leakiness but also on the magnitude of driving forces, principally wind speed and indoor-outdoor temperature differences, that drive air flow across the building shell. However, the *air flow rate at a given pressure drop* is a property of the building alone; hence, this is the measure used to quantify building leakiness. Air flow rate at a specified pressure drop is also referred to as the building's *leakage parameter.*

This project comprised five key tasks:

1. **Literature review.** Locate publications and public data sources related to indoor-outdoor air leakage for commercial buildings and apartments, either in California or elsewhere. Compile a database.
2. **Interviews.** Contact experts who have performed testing or measurement of air exchange rates. Ask about sources of private data, e.g., from companies that "commission" commercial heating, ventilation, and air conditioning (HVAC) systems. If appropriate, contact those companies and request data. Through these discussions and the literature review conducted in Task 1, determine the current state of knowledge about commercial building and apartment leakiness.
3. **Characterize multi-family housing stock.** Examine data from the U.S. Department of Energy's Residential Energy Consumption Survey, the American Housing Survey, and other sources, to characterize the existing multi-family building stock in California, in terms of age, building size, building type (multi-use or residential), and other factors. Compare results to the coverage of available air infiltration data to determine which particular building types are over- or under-represented in the data.
4. **Analysis.** Looking at all data obtained for commercial and apartment buildings, compare leakage parameters to building characteristics to determine any trends—i.e., characterize leakiness distributions by building use, size, construction, age, etc.
5. **Reporting.** Summarize the current knowledge of air exchange rates as a function of building type and age, and identify gaps in the current knowledge.

2.0 Project Approach

2.1. Data Collection

The project began with a literature search to determine the current state of knowledge concerning commercial building and apartment airtightness. Although this report is oriented towards California buildings in particular, the research team discovered that there are almost no data on California buildings, and thus little knowledge about these issues that is specific to the state. Consequently, the search for both data and reported data analyses was broadened to the entire U.S., then the U.S. and Canada, and finally the U.S., Canada, and Europe.

This effort obtained all of the published data concerning leakage measurements in apartment buildings and commercial buildings (as defined in Chapter 1), from approximately the last twenty years. The data search was restricted to publications that featured actual measurements of leakage from entire buildings, as opposed to measurements of individual leakage elements (such as duct or window leakage) or computer modeling or prediction of leakage. Some publications containing leakage measurements appear in a "gray literature" of conference proceedings or agency reports, rather than publications in refereed archival journals. These reports were included when the research team was aware of them, but it is likely that, particularly for apartments, there are some gray-literature data that was not found. However, it is unlikely that the project failed to obtain large amounts of apartment data,[1] and the commercial building data set is thought to be comprehensive.[2]

2.2. Data Analysis

There are at least two approaches to measuring or describing air exchange in buildings. One is to focus on the air exchange rate: how much air enters the building during a given time period. (This is equal to the amount of air that leaves the building in the same time period). The air exchange rate depends not just on the building itself, but also on the driving forces that the building is experiencing, that force air into the building. The dominant driving forces, other

1. The authors spoke with Richard Diamond, Craig Wray, and Darryl Dickerhoff, all of whom are colleagues in the Indoor Environment Department of Lawrence Berkeley National Laboratory and all of whom are experts in building leakage measurements. They were able to help find additional apartment data. More apartment data seem to have escaped publication than is the case for commercial buildings, so it is possible that there are some apartment data that were not obtained. However, Wray and Dickerhoff, who have extensive contacts in this area of research, do not believe that there are large amounts of such data beyond what was found.

2. The authors have more confidence that the project obtained a comprehensive set of measurements for commercial buildings than for apartments. The research team spoke with Andrew Persily and Steven Emmerich of the National Institute of Standards and Technology (NIST), who have wide-ranging, ongoing contacts with commercial building leakage researchers. Persily and Emmerich confirmed that the project database contained almost all of their data, plus some that they did not have. They did have some new measurements from an Army Corps of Engineers database that the research team had not been aware of, which were then incorporated into the project's data set (with identification of the specific buildings removed at the request of the Corps).

than operation of the ventilation system, are (1) wind and (2) the "stack effect": if the air in the building is warmer than the outdoor air, buoyancy forces push it upward so that air tends to escape from the top of the building and to be replaced by incoming air entering the lower parts of the building, a situation that is reversed if the indoor-outdoor temperature difference is reversed. This project generally excluded consideration of the heating, ventilation, and air conditioning (HVAC) system (if any) because the air brought into the building through its operation is provided intentionally. This report focuses on unintended air infiltration: how much air enters the building if the HVAC is turned off, or, as with many apartment buildings and a few commercial buildings, if the building has no HVAC system. A brief discussion of HVAC-induced air exchange in commercial buildings is provided.

The other approach to quantifying or describing air exchange is to focus on parameters that describe the building itself, rather than the combined effect of the building and the driving forces. Experimentally, this is usually done by using a fan or "blower door" to pressurize the building to a specified level relative to the outdoors, and recording how much air must be provided to maintain that pressure. ASTM (formerly known as the American Society for Testing and Materials) has published standards (ASTM 1999) for performing such tests; in addition, Baylon and Heller (1998) have proposed methods specifically for small multifamily buildings, and Brennan et al. (1992) have recommended methods specifically for school buildings. Most experiments reported in the literature applied a differential pressure of 50 pascals (Pa), but some used 4 or 10 Pa. In these cases, the project team adjusted the results, through application of Equation 1 (see Section 3.2.1), to report the airflow (per unit area of building envelope) for a 50 Pa indoor-outdoor pressure difference.

After collecting the data, the research team performed statistical analyses to look for systematic variation of building leakiness as a function of various factors, such as height, age, construction materials, building purpose, etc. The analysis used a statistical technique known as "Bayesian hierarchical modeling" (see Gelman et al. 1995, Chapter 8, for example) to address problems caused by small sample sizes. The disappointingly small amount of data, and the fact that the data were not statistically representative of California's building stock, precluded making definitive quantitative statements about building leakiness.

The research team also examined data from the U.S. Department of Energy's Commercial Building Energy Consumption Survey, or CBECS (EIA 2003), to compare the types of buildings in the project's commercial building leakage database to the buildings in CBECS and thereby identify major data gaps.

The research team had originally contemplated summarizing data from residential surveys, to identify gaps in apartment building data as well, but discovered that there are so few apartment building data that there is no point identifying "gaps": there is *no* category of apartment buildings for which data are adequate to make statements about leakiness with any degree of confidence. This is discussed in more detail in Chapter 3.

3.0 Project Outcomes

Section 3.1 discusses the current state of knowledge about apartment and commercial building leakage, as determined through a literature search and discussions with experts in the field. Section 3.2 presents the results of new data analyses to attempt to address some of the major questions of interest.

3.1. Current Knowledge

Buildings are often divided into two categories: places where people live, called "residential" buildings, and places where people work, which this report will call "commercial buildings" although this is not technically the correct term (since government buildings, schools, and other non-commercial buildings are also workplaces).

Residential buildings can be divided into (1) single-family houses and (2) multi-family residences. Commercial buildings (as defined above) can be divided into many sub-categories: office buildings, small or large retail buildings, schools, etc.

Of all of the many categories and sub-categories of buildings, the only category for which air exchange rates and leakage parameters are well known is single-family detached houses. Vast amounts of data are available for single-family homes, mostly as a result of "energy audit" programs that seek to quantify house leakiness or identify leaky homes in order to implement energy efficiency programs. The available data are subject to selection bias and other problems, but the overall picture is characterized well enough that most practical questions that rely on knowledge of the statistical distribution of house leakage parameters can be answered (Chan et al. 2005).

In contrast, the state of knowledge regarding commercial and apartment buildings is poor: data are sparse, and there are complications in both measuring and conceptualizing building leakage because some commercial buildings are compartmentalized into discrete stores, offices, etc., in such a way that air exchange between compartments can interact with air exchange between the building and the outdoors. One implication of the interaction between indoor flow and indoor-outdoor air exchange is that it is difficult to predict the air exchange rate as a function of wind, indoor-outdoor temperature, and building leakage parameters. This contrasts with single-family homes, with their small absolute size and large surface-to-volume ratio, where very simple formulae relate the environmental conditions and leakage parameter to the air change rate. Such is not the case for more complex buildings.

Persily (1999) has shown that, contrary to the expectation of some experts, air infiltration is significant in commercial buildings. VanBronkhorst et al. (1995) estimate that infiltration accounts for 10% to 20% of the heating load in all office buildings nationwide, although they estimate it to have little effect on cooling loads, in part because of lower winds and lower indoor-outdoor absolute temperature difference in summer compared to winter.

Although air infiltration in commercial buildings is significant, the air exchange rate due to HVAC operation is almost always larger than the air infiltration rate (Persily 1999; VanBronkhorst et al. 1995). Therefore, removal of indoor pollutants, delivery of outdoor pollutants, and energy costs are largely determined by the details of HVAC design and operation. Moreover, since HVAC systems often mix air from different parts of the building, and deliver outdoor air approximately equally to different parts of the building, predicting indoor exposures to outdoor pollutants can be done fairly accurately using knowledge of HVAC operation alone. For these reasons it is somewhat understandable that little effort has gone into modeling air infiltration rates in commercial buildings, or into experiments to determine the relationship between building leakiness and air exchange for commercial buildings. Essentially, researchers and funders have collectively decided that since, for commercial buildings, HVAC operation is generally more important than infiltration, most effort spent in better understanding infiltration is not worth it. Still, some work on predicting commercial building infiltration from leakiness, temperature, and wind has been performed. The best, and best-validated, work is from Shaw and Tamura (1977); that work is summarized in Appendix A, most of which is expected to appear in the dissertation of R. Chan (Chan 2006).

Although the near neglect of the relationship between leakiness and infiltration in commercial buildings is understandable for reasons discussed above, the same cannot be said for the relationship between leakiness and infiltration in apartments. Many apartment buildings do not have central HVAC systems, so infiltration is a major contributor to overall air exchange rates. In buildings without HVAC systems, if people keep their windows closed and do not operate window air conditioners, infiltration is the only process of indoor-outdoor air exchange. So infiltration is a very important phenomenon in apartment buildings, and it is somewhat surprising, and disappointing, that more quantitative work on the relationship between leakiness and air exchange rates has not been performed. The authors speculate that small apartment buildings and row houses might reasonably be modeled similarly to single-family houses and that larger buildings might be modeled using the Shaw and Tamura model that was designed for commercial buildings, but there are no experimental data to support this assumption.

3.2. Analysis of Available Data

In an extensive review of the literature, the research team compiled all published articles that could be found that reported measured air exchange rates or leakage parameters in commercial buildings or in apartments. This yielded:

1. Data on 267 commercial buildings in five developed countries. Of these, 164 buildings are from the U.S. (but none are from California); the others are from Canada, the UK, Sweden, and France. Thus, most buildings are from areas with a harsher climate than California's. The tested buildings are mostly offices (18%), industrial/ warehouses (13%), and schools (27%), followed by small retail (7%) and strip malls (6%), recreational buildings and auditoria (7%), and with the remaining 21% being supermarkets, public buildings, restaurants, lodging (hotels and motels), health care facilities, malls, and others. Half of the buildings are classified as having masonry

construction (including concrete block). Metal frame/metal panel and concrete panel/tilt-up are also common among the office and warehouse/industrial buildings tested. All of the raw data are presented in Appendix C.

2. Data from 162 apartments/living units in 78 buildings in the U.S. and Canada. Only four of the apartments are in California, from two buildings in Oakland. In some of the apartment buildings, only the total leakage was measured (not the leakage from individual apartments); in others, measurements were made in individual apartments. In some cases researchers measured the leakage from one apartment to another within a building, in others they did not. In some cases air exchange rates were measured, while in other cases the air flow rate at a given pressure drop was measured. All of the raw data are presented in Appendix D.

In addition to performing the literature search, the project team also communicated, by email or phone, with several researchers who perform building leakage measurements or analyze building leakage data: Andrew Persily and Steve Emmerich from the National Institute of Standards and Technology, and Max Sherman from Lawrence Berkeley National Laboratory. Emmerich was able to provide unpublished data collected by the U.S. Army Corps of Engineers. This data set included leakiness measurements for 75 commercial buildings (which are counted as part of the 267 commercial buildings analyzed). Schools represented about half of these measurements, while the other half comprised community center and health care buildings. Most of these buildings were classified as masonry or metal frame construction.

3.2.1. Commercial Buildings Data Analysis

The commercial building leakiness measurements used in this analysis were compiled from 15 different studies published in journal articles and conference proceedings. The studies represent measurements from several countries with the majority of measurements from the United States. Most leakiness measurements were obtained for energy efficiency programs and focus on certain types of buildings in certain areas. The largest single set of measured leakage data is 69 buildings from the Florida Solar Energy Center (Cummings et al. 1996). These are buildings located in Florida and include many different building types, such as offices, schools, and retail.[3] Two other studies measured different types of buildings (Litvak et al. 2001; Dumont 2000), but most focus on certain building types. Two studies measured leakage in schools (Shaw and Jones 1979; Brennan et al. 1992), one measured supermarkets and malls (Shaw 1981), four measured offices (Shaw and Reardon 1974; Grot and Persily 1986; Potter, Jones, and Booth 1995; Perera and Tull 1989), and five measured industrial warehouses (Lundin 1986; Potter and Jones 1992; Fleury et al. 1998; Perera et al. 1997; Jones and Powell 1994). The limited data used in this

3. It is possible that building design or construction techniques vary regionally, so that California buildings could differ systematically from those elsewhere in the country. Specifically, one might expect that buildings in mild climates such as California's might be designed or built with less concern about minimizing air leakage. The available data do not allow us to investigate this issue in detail, but there is no evidence of substantial regional variation. Variation between regions of the country appears to be much less than the variation between buildings within a region.

analysis are not statistically representative of all commercial buildings: buildings were sampled opportunistically rather than as part of a systematic scheme.

The commercial building data include the rate of air exfiltration when the building is pressurized to 4, 10, 50, or 75 pascals relative to outdoors. This is a measure of the "leakiness" of the building. Leakiness is related to the building's air exchange rate, but it is not the only or indeed the largest parameter controlling the air exchange rate for commercial buildings, which is normally dominated by the effects of the building's ventilation system. In a building without a ventilation system, or with a system that is not operating, the air exchange rate depends on both the leakiness of the building in addition to the magnitude of the forces that drive indoor-outdoor air exchange: principally, wind forces and thermal buoyancy forces.

Most of the buildings in the leakiness database were built between 1960 and 2000, centering at around 1980. Sixty percent of the buildings have a footprint area < 1000 m^2. About 75% of the buildings are single story, but there are also 12 buildings that have 10 stories or more. Table 1 shows the distribution of each of these characteristics among the buildings sampled, both in absolute numbers and as a percentage of the total database.

Table 1. Number (and percentage) of buildings in the commercial buildings database, by building footprint area and building height in stories

	Footprint Area		All Footprint Areas
Building Height	< 1000 m^2	≥ 1000 m^2	
1 story	129 (48)	79 (30)	208 (78)
1.5 to 3 stories	20 (7)	13 (5)	33 (12)
3.5 to 5 stories	2 (1)	7 (3)	9 (3)
> 5 stories	9 (3)	8 (3)	17 (6)
All heights	160 (60)	107 (40)	267 (100)

For the analysis, the project used reported leakage area measurements to determine the air flow rate (in liters per second) per square meter of building envelope, for an indoor-outdoor pressure difference of $\Delta P = 50$ Pa, where the building envelope area, A (m^2), includes both the vertical walls and the roof. In cases in which the experimental data were generated from a ΔP other than 50 Pa, results were adjusted with the following relationship:

$$Q = C \cdot A \cdot \Delta P^n \qquad \text{Eqn. 1}$$

where Q (m^3/s) is the airflow rate needed to pressurize the building to a pressure difference of ΔP (Pa) with respect to the outdoors, n is the flow exponent, and C is the flow coefficient (i.e., the leakage parameter).

Using pairs of Q and ΔP measurements, C and the flow exponent n can be determined through a fitting procedure. According to the orifice flow equation (see Munson et al., 1998, for example), the theoretical limit of n is between 0.5 and 1. When a building is leaky, resistance from inertia is the largest effect restricting the airflow through the building envelope, and n approaches 0.5. On the other hand, when a building is tight, there is little airflow through the building envelope, and the flow resistance is dominated by drag through the building's cracks and n approaches 1.

The correlation coefficient between C and n was found to be -0.44 with a 95% confidence interval of -0.55 to -0.32. In AIVC Technical Note 44 "Numerical Data for Air Infiltration and Natural Ventilation Calculations" (1994), n is found to correlate with leakage with a correlation coefficient of -0.36, which is similar to what was found by this study. The distribution of n among buildings is also consistent with earlier studies: roughly normal, with a mean of 0.62. For this analysis the effective leakage area from each study was recalibrated to a pressure differential of 50 Pa and normalized to the surface area of the measured building. The power law flow exponent, n, ranged for 0.3 to 0.9, and was assumed to be 0.65 when not reported in the original publication.

For the 267 commercial buildings tested, the normalized building leakage (i.e., the building leakiness) is roughly lognormally distributed, with a geometric mean (GM) of about 4 L/(s·m^2) at 50 Pa, and a geometric standard deviation (GSD) of about 2.3. Figure 1 shows a histogram of the distribution of the logarithms (base 10) of the data.

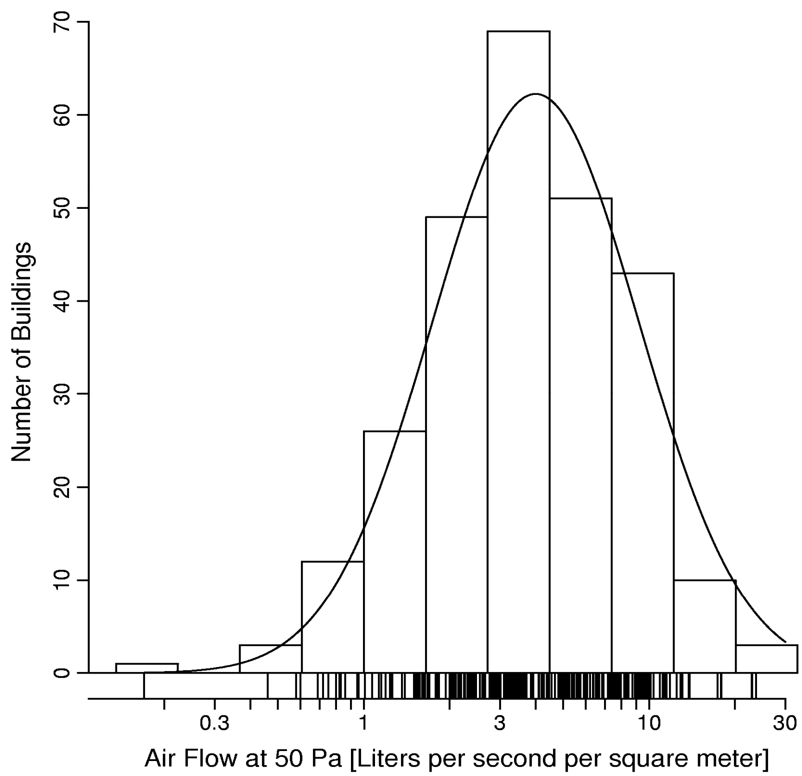

Figure 1. Histogram of air flow (liters per second per square meter of building shell) at 50 Pa indoor-outdoor pressure difference, for the 267 buildings in the commercial buildings database. These data do not constitute a representative sample of all commercial buildings. The distribution is approximately lognormal, with a geometric mean (GM) of 4 L/(s·m^2) and a geometric standard deviation (GSD) of 2.3.

In contrast with the commercial building distribution, the project team's recent analysis of the air leakage of U.S. single-family houses (Chan et al. 2005) found that the leakage follows a lognormal distribution with a GM of 2.6 L/(s·m²), and a GSD of 1.6, at a 50 Pa indoor-outdoor pressure difference. Thus, based on this cursory summary of the data, commercial buildings seem to be somewhat leakier than single-family houses, and also to have leakiness that is more variable than single-family homes.

On the basis of published information about the buildings that were measured, the current project classified each building according to usage (e.g., school, retail, etc.) and construction type (masonry, steel frame, etc.). "Manufactured building" refers to trailers or portable structures. Inevitably, there is some ambiguity in the classification of building usage and construction types. Classifications were based on those used in the original studies, but interpretation was required for some entries that did not perfectly match any of the categories. Table 2 summarizes the number of buildings in each classification and construction type, and the fraction of the total database that these numbers represent. Table 3, later in this section, presents similar information for the building distribution in California, Oregon, and Washington.

Table 2: Number of buildings (and, in parentheses, percentage of all buildings) in the project's commercial buildings database, by construction type and usage classification

	Masonry	Frame/ Masonry	Concrete Panel/ Tilt-up	Metal Frame/ Metal Panel	Curtain-wall	Manu-factured	Wood Frame/ Frame	N/A	Total
Education	52 (19)			4 (1)		1 (0)	1 (0)	14 (5)	72 (27)
Super-market	7 (3)		2 (1)						9 (3)
Mall	1 (0)								1 (0)
Office	20 (7)		13 (5)	9 (3)	2 (1)	4 (1)	1 (0)		49 (18)
Warehouse/ Industrial	6 (2)		6 (2)	20 (7)				3 (1)	35 (13)
Small Retail	10 (4)	1 (0)		2 (7)			1 (0)	4 (1)	18 (7)
Strip Mall		12 (4)					4		16 (6)
Health Care	8 (3)			2 (2)			1 (0)	1 (0)	12 (4)
Public Building	8 (3)	1 (0)		5 (2)				5 (2)	19 (7)
Recreation/ Auditorium	15 (6)						1 (0)	2 (1)	18 (7)
Restaurant	4 (1)	1 (0)					2 (1)		7 (3)
Lodging	5 (2)						2 (1)		7 (3)
N/A				1 (0)				3 (1)	4 (1)
Total	136 (51)	15 (6)	21 (8)	43 (16)	2 (1)	5 (2)	13 (5)	32 (12)	267 (100)

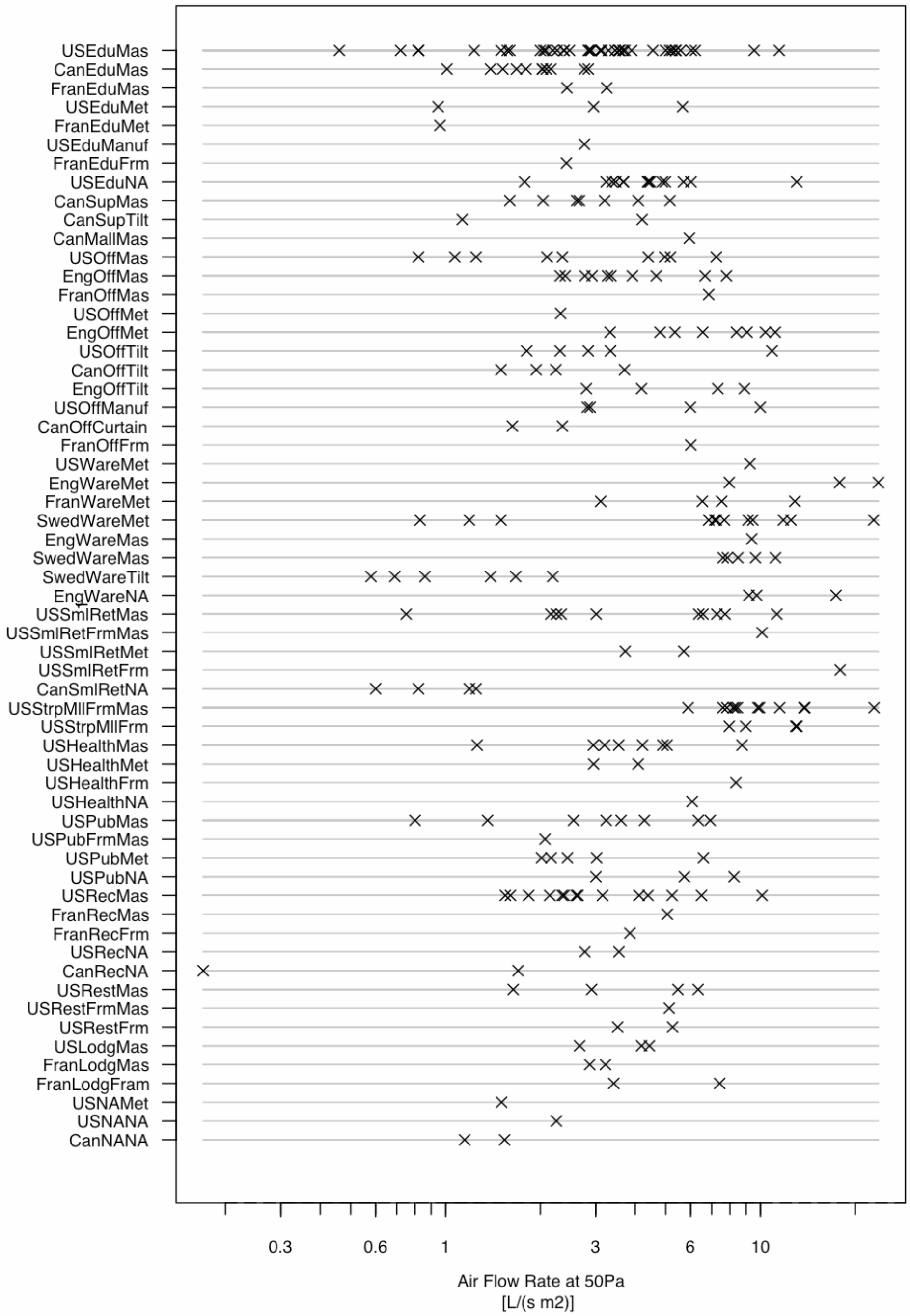

Figure 2. Air flow rate (liters per second, per square meter of building shell) at a 50 Pa indoor-outdoor pressure difference, for each building in the database, grouped by building usage and construction type. X-axis is a logarithmic scale. Countries are: U.S. = United States, Swe = Sweden, Fran = France, Can = Canada. Usage categories are: Edu = Education, Off = Office, Ware = Warehouse, SmlRet = Small Retail, Pub = Public Assembly, Lodg = Lodging, StrpMll = Strip Mall, Health = Health Care, Rest = Restaurant. Construction categories are: Mas = Masonry, Tilt = Tilt-up, Met = Metal Panel, Mas = Masonry, Frm = Frame, NA = unknown.

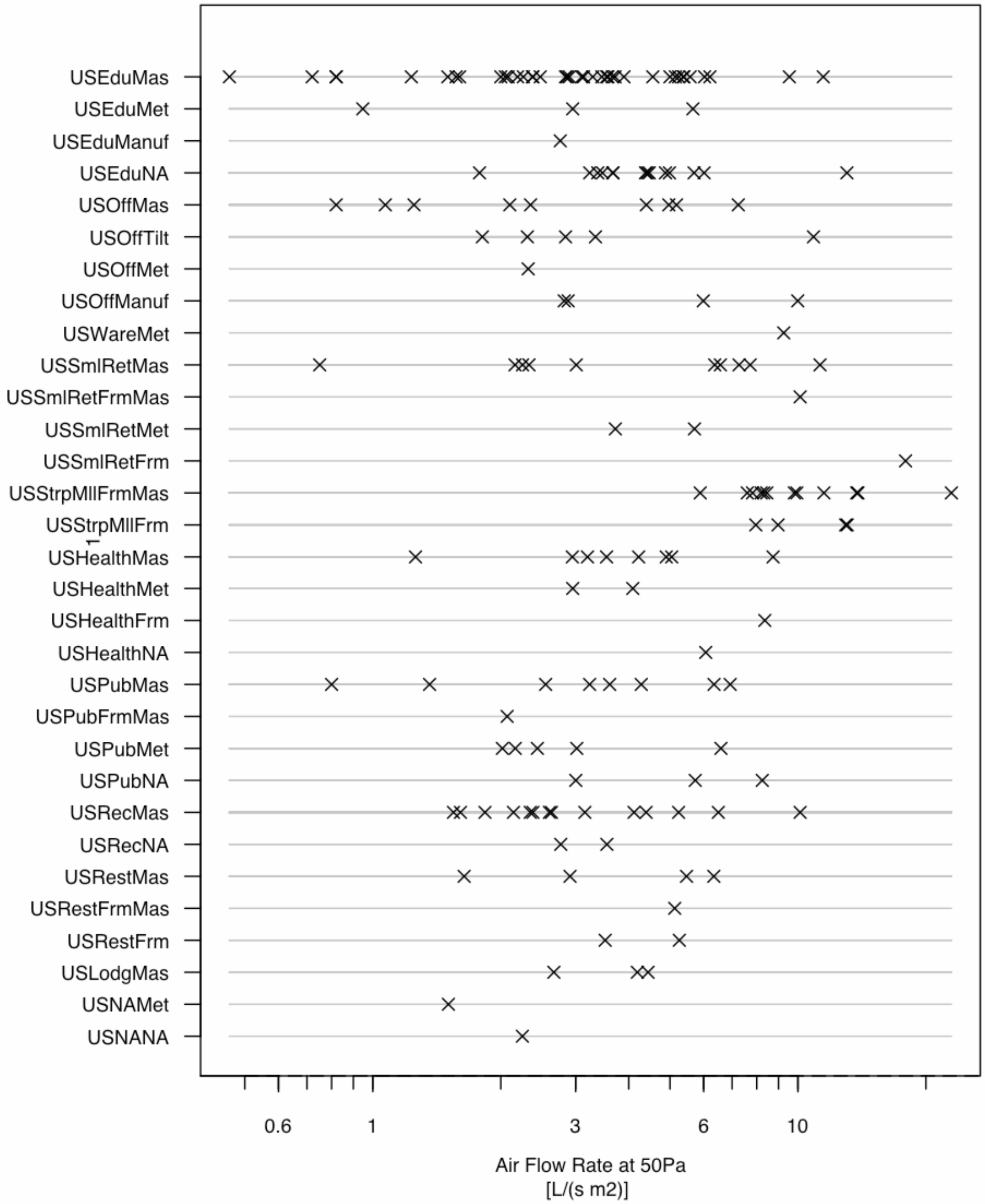

Figure 3. Same as Figure 2, for U.S. buildings only: Air flow rate (liters per second, per square meter of building shell) at a 50 Pa indoor-outdoor pressure difference, for different types of buildings in the United States. X-axis uses a logarithmic scale. Usage categories are: Edu = Education, Off = Office, Ware = Warehouse, SmlRet = Small Retail, Pub = Public Assembly, Lodg = Lodging, StrpMll = Strip Mall, Health = Health Care, Rest = Restaurant. Construction categories are: Mas = Masonry, Tilt = Tilt-up, Met = Metal Panel, Mas = Masonry, Frm = Frame, NA = unknown.

Figure 2 shows the total flow rate at 50 pascals, normalized to the building surface area, for each subtype of building for which data could be found. For instance, each x on the uppermost line (USEduMas) indicates the logarithm of the flow rate at 50 Pa for U.S. "educational" buildings with masonry construction. The x's are spread rather widely along the x-axis, indicating that some of these buildings are much less leaky than others (farther right indicates higher leakiness). Figure 3 shows just the U.S. data.

As can be seen in Figures 2 and 3, there is some evidence that a few building types are leakier than others. The real standout is U.S. frame-masonry strip malls (middle of Figure 3), for which reported leakiness is very high (a geometric mean of 9 L/(s·m^2) at 50 Pa). However, the experimental method used to generate these measurements included leakage to other units within the building, not just to the outdoors, so the leakiness to the outdoors is probably much less than reported. For this reason, strip malls are excluded from many of the following discussions.

Ignoring strip malls, and considering only the U.S. buildings, there is, perhaps surprisingly, little evidence of systematic variation of leakiness with building type or construction type. However, the data set's statistical power to address this issue is quite poor: in the U.S., excluding strip malls, there are only four combinations of building type and construction method for which 10 or more measurements are available. The combination of building type and construction method will be referred to as the "building category." Figure 4 shows the observed geometric mean for the U.S. building categories with 8 or more observations, excluding strip malls. Confidence bounds (one multiplicative standard error), based purely on small-sample error and not accounting for potential sample bias, are shown with error bars. Only the U.S. educational buildings with unknown (NA) building type have a geometric mean that is statistically significantly different (at the $p < 0.05$ level) from the overall geometric mean for the data.

However, restricting the analysis to the well-sampled building categories results in excluding more than 60% of the data. What's more, such a restriction fails to take advantage of the potential for a relationship between various building categories; for instance, masonry buildings might be expected to group together somewhat in leakiness and metal-frame buildings might do the same, and so on. Some similarity would also be expected between U.S. masonry office buildings and similar buildings in other countries. To explore these possibilities and quantify the results, the project team used a standard but somewhat complicated statistical method, known as Bayesian Hierarchical Modeling (or Multi-level Modeling), results of which are discussed below and are presented in detail in Appendix B.

Some of the variability in commercial building leakiness was modeled by correlating building characteristics with the air leakage coefficient measured. There are two types of explanatory variables in the data set: continuous and categorical. Continuous explanatory variables include the year built, floor area, and height of the building. Categorical explanatory variables include the functional and construction type of the building. This project only examined the variables listed here, but there are other factors that might affect the air leakage of a building, for which no data were available. For example, differences in building codes and practices between countries, due to climatic concerns or other issues, can affect the airtightness of buildings. How carefully the building was constructed and maintained can also affect air leakage.

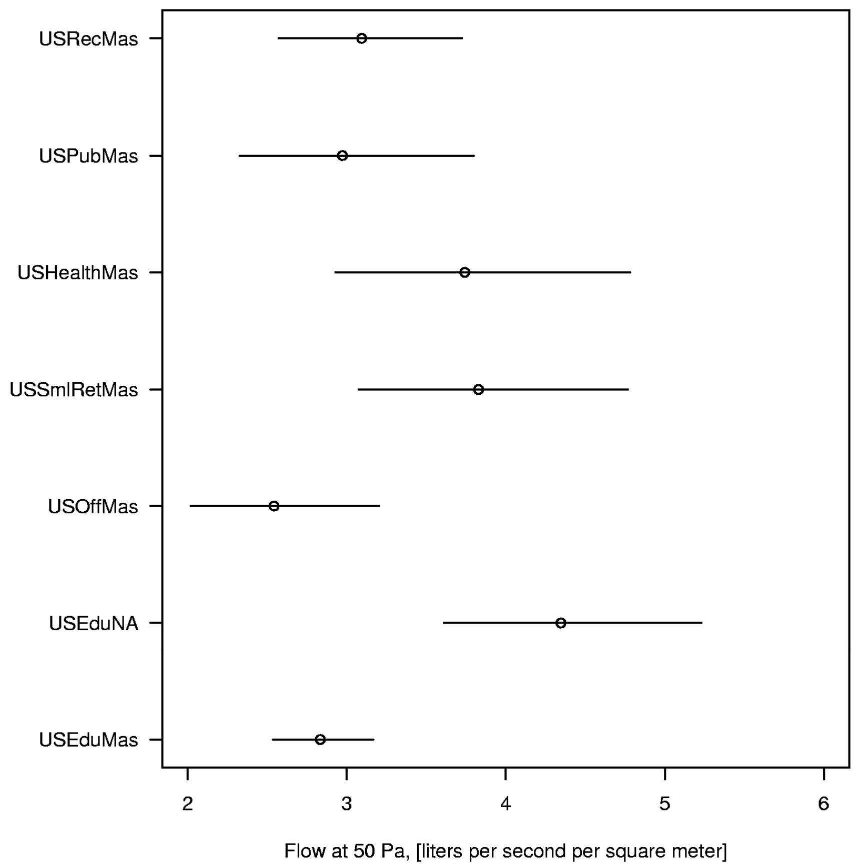

Figure 4: Observed geometric mean air flow rate (liters per second, per square meter of building shell) at a 50 Pa indoor-outdoor pressure difference, with 68% confidence intervals, for U.S. building categories with at least eight measurements, excluding strip malls. Usage categories are: Edu = Education, Off = Office, SmlRet = Small Retail, Pub = Public Assembly, Health = Health Care. Construction categories are: Mas = Masonry, NA = unknown.

Presenting the raw data in more detail, Figures 5 and 6 display the building leakiness data by function and construction type (similarly to Figure 2 and Figure 3), but now using plotting symbols that distinguish the buildings by height and by footprint area. From visual inspection, there is little evidence of a substantial relationship between height and leakage, footprint and leakage, or building age (or year built) and leakage (see Figure 8). Nevertheless, in addition to building categories, footprint and height categories were included in the statistical analyses.

The main results, listed below, concern multivariate analyses that consider all of the available explanatory variables together (in addition, some univariate comparisons were also performed):

1. For buildings with footprint area greater than or equal to 1000 square meters (n=107), the geometric mean flow rate at 50 Pa was 4.5 L per second per square meter of building shell. For buildings with footprint area less than 1000 square meters (n=160) the geometric mean flow rate at 50 Pa was 2.6 L per second per square meter of building shell.
2. For buildings with 5 or more floors (n=26), the geometric mean flow rate at 50 Pa was 3.3 L per second per square meter of building shell. For buildings with fewer than 5 floors (n=241), the geometric mean flow rate at 50 Pa was approximately the same, 3.7 L per second per square meter of building shell.
3. For buildings built in 1986 or later (n=131), the geometric mean flow rate at 50 Pa was 3.8 L per second per square meter of building shell. For buildings built before 1986 (n=136), the geometric mean flow rate at 50 Pa was approximately the same, 3.5 L per second per square meter of building shell.

Multivariate analyses (i.e., including more than one explanatory variable at a time) suggest that there may be effects associated with building footprint and height, but in no case did the parameters associated with building age indicate the presence of a substantial building age effect, so age was excluded from the main analysis. The lack of evidence for an effect related to building age may be surprising, given that new single-family homes have become much more airtight over the past twenty years (Chan et al. 2005). However, there is little reason to believe that airtightness in commercial buildings must increase just because single-family residential airtightness increases: first, construction techniques for most commercial buildings are very different from those for houses, and second, cost-conscious homebuyers have more incentive to save than do cost-conscious business owners since less than 1% of a typical company's payroll is spent on heating and cooling. Persily (1999) has previously noted that although many researchers and laypeople assume that commercial buildings have become more airtight in recent years, there is no evidence that this is true. Project findings suggest, like Persily, that commercial buildings from the 1990s are about the same in terms of leakiness as those from earlier decades. Effects related to building age could also be difficult to interpret to a variety of effects such as changes in leakiness (or mechanical ventilation rates) due to renovations; shell or duct leakage that changes with time due to degradation of caulking or duct tape (an effect that might depend on both building design and construction details); and so on.

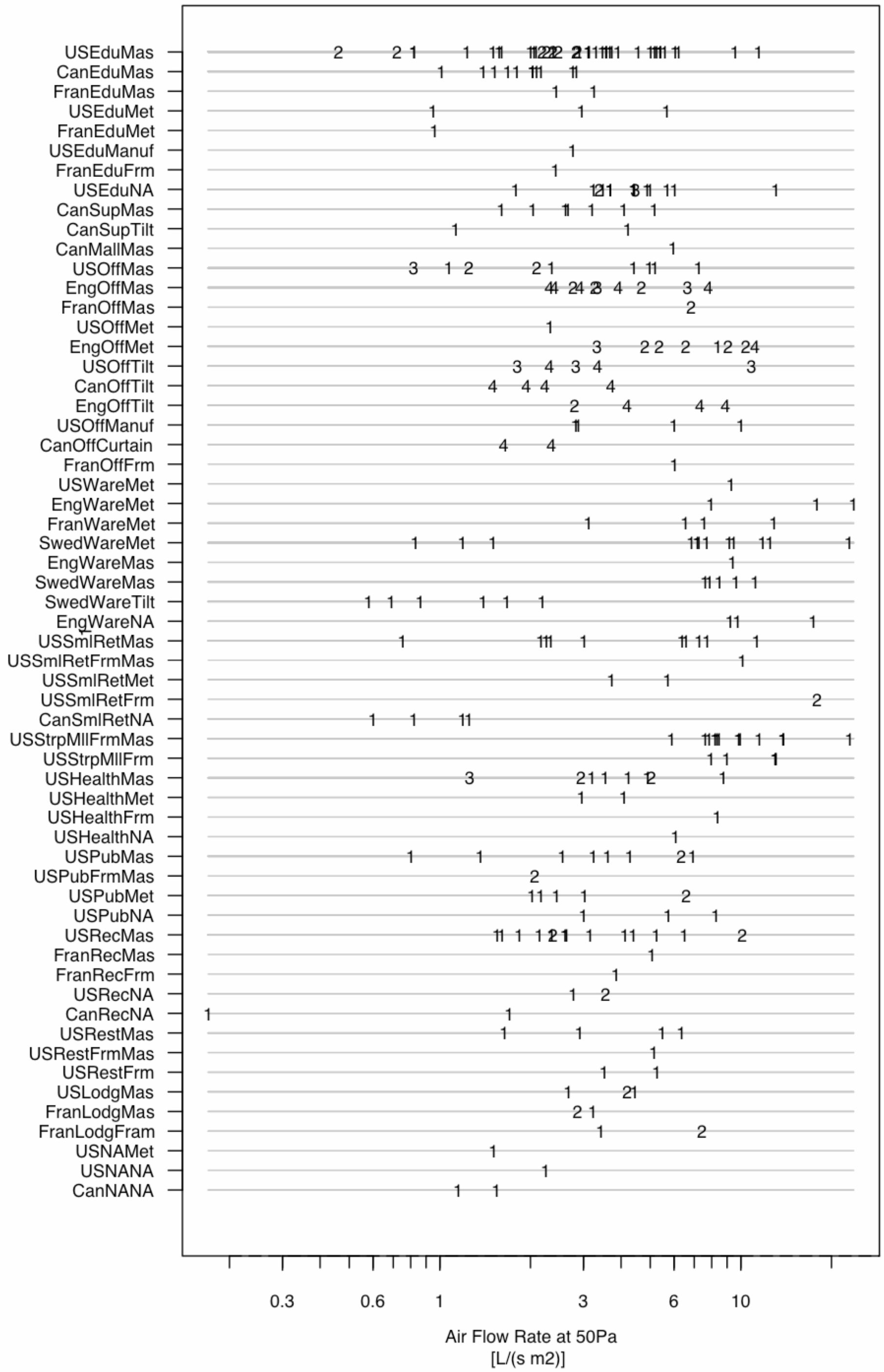

Figure 5. Air flow rate (liters per second, per square meter of building shell) at a 50 Pa indoor-outdoor pressure difference, for each building in the commercial buildings database, grouped by building usage and construction type, with indication of building height. Building height classes are: 1=single story, 2 = 2–3 stories, 3 = 4–5 stories, 4 = 6 or more stories. See Figure 7 as well.

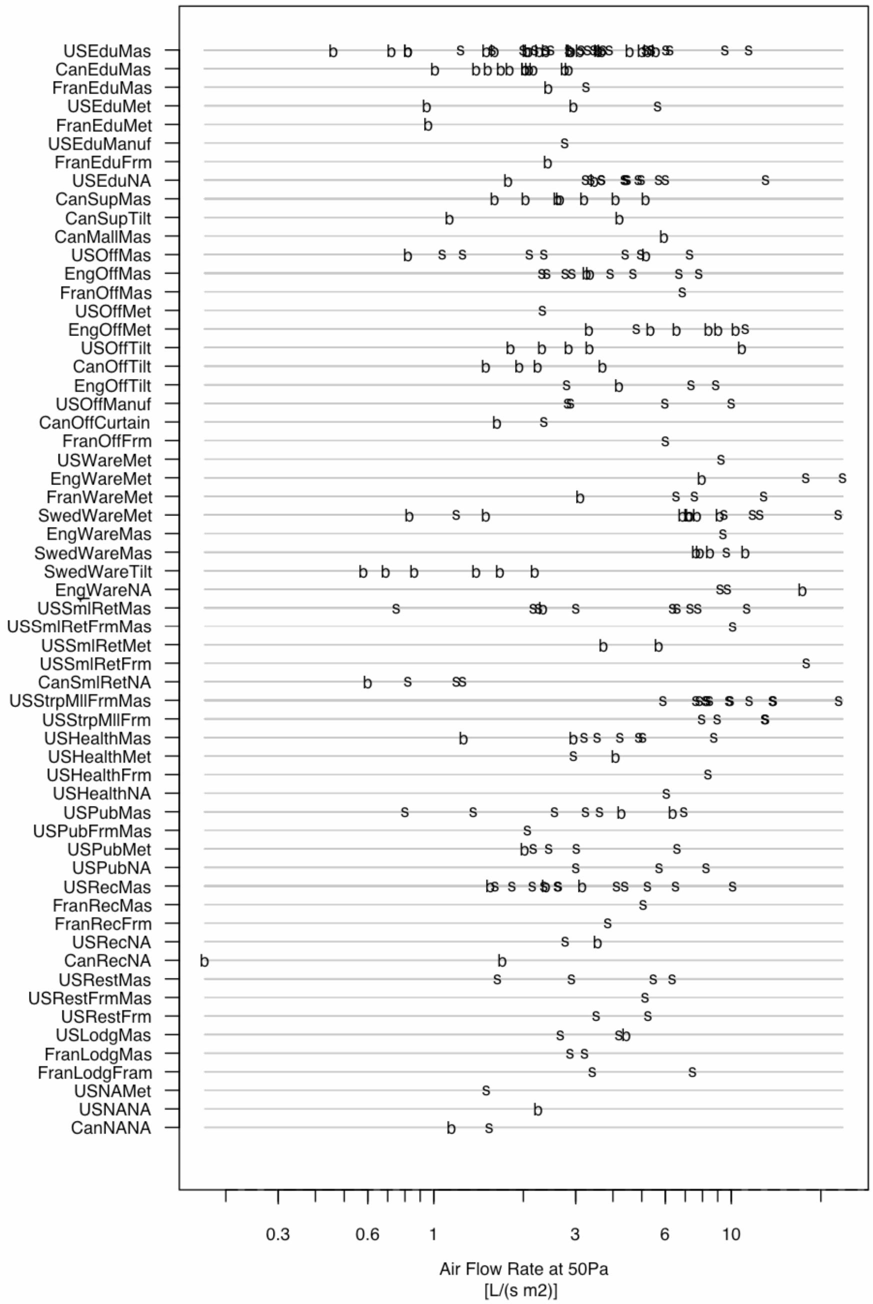

Figure 6. Air flow rate (liters per second, per square meter of building shell) at a 50 Pa indoor-outdoor pressure difference, for each building in the database, grouped by building usage and construction type, with indication of building footprint. The symbol "b" represents "big" footprint (1000 m^2 or larger), "s" represents "small" footprint (under 1000 m^2). Symbols for U.S. educational masonry buildings (top row) are obscured by over-printing, but contain a mix of "b" and "s" throughout the central part of the data.

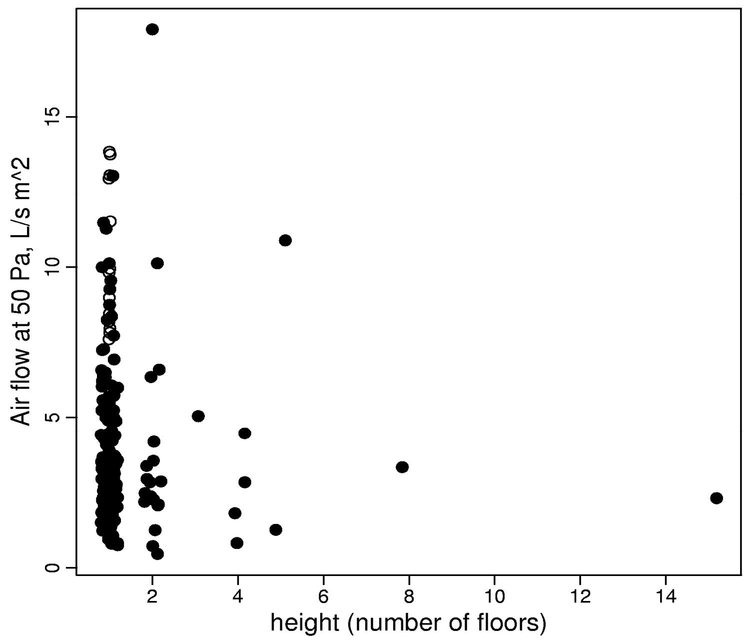

Figure 7. Air flow rate at 50 Pa indoor-outdoor pressure difference, in liters per second per square meter of building shell, versus number of floors in the building. Some horizontal "noise" has been added to separate the points. Measurements in strip malls are shown with open circles; all other data are solid circles.

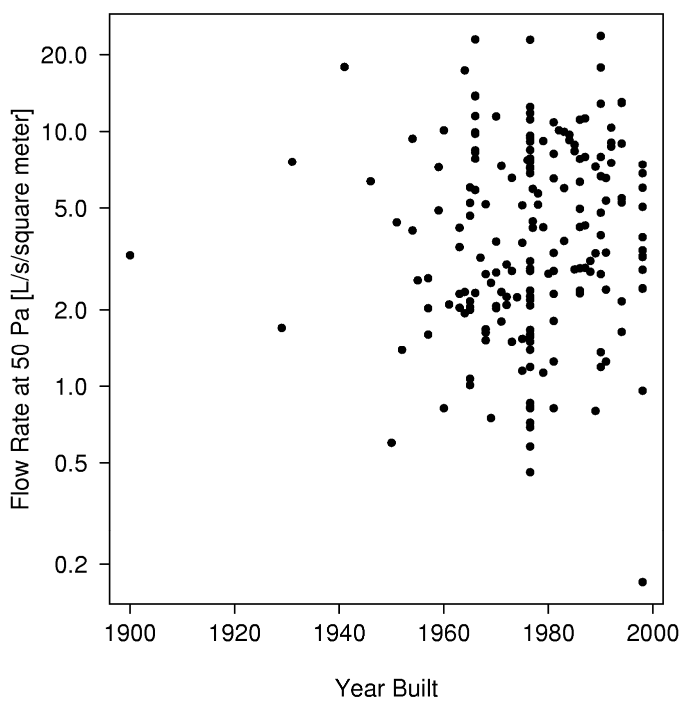

Figure 8. Air flow rate at 50 Pa indoor-outdoor pressure difference, in liters per second per square meter of building shell, versus year in which the building was built. The y-axis is a logarithmic scale.

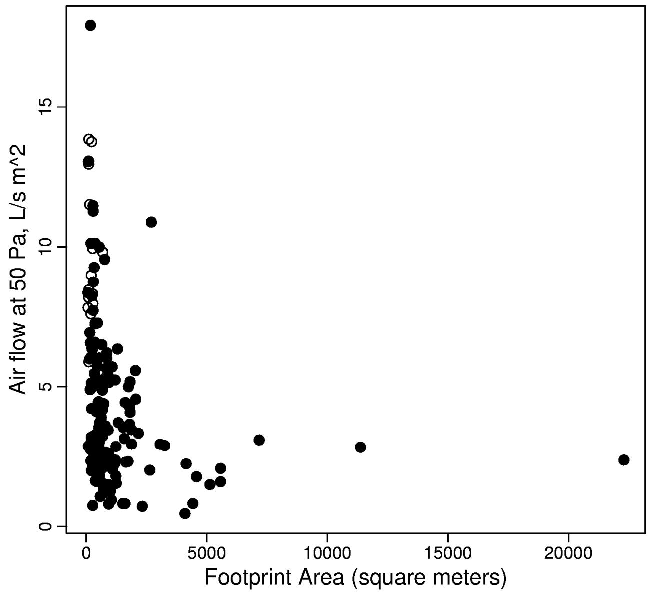

Figure 9. Air flow rate at 50 Pa indoor-outdoor pressure difference, in liters per second per square meter of building shell, versus footprint area of the building. Open circles are used for strip malls, solid circles for all other data.

The analysis looked for systematic variation between construction materials, building types, building heights, and the country in which the building is located. For each building, known parameters are its height, volume, envelope construction material or construction type (metal frame, masonry, etc.), and the category of activity that takes place in the building (education, retail, etc.). In some cases, the year of construction is also known.

Details of analytical methods and the resulting parameter estimates are presented in Appendix B. As discussed above, the project data set is not statistically representative and sample sizes are small, so the exact numerical parameter estimates have not been emphasized. Instead, the report summarizes general results that are likely to be true of the general building stock.

The analysis suggests the following conclusions (ignoring strip malls for reasons discussed above):

1. Within a given building activity (education, retail, etc.) there appears to be little systematic variation with construction type. At a 50 Pa indoor-outdoor pressure difference, a typical building of a "leaky" construction type may experience flow about 5% to 15% higher per unit area of building envelope than a typical building; there is some evidence that frame and frame-masonry construction are slightly leakier than others. This amount of variation between construction types is much less than the amount of variability within a construction type.
2. Within a given construction type (metal-frame, masonry, etc.) there is some evidence that schools and public assembly buildings tend to be tighter than average and that

warehouses tend to be leakier than average. At a 50 Pa indoor-outdoor pressure difference, a typical building of a "leaky" building category might experience air flow about 20% to 40% higher per unit area of building envelope than a building in a "tight" building category.

3. For a given building category, buildings with small "footprints" (i.e., small roof area), under 1000 m^2, tend to be 25% to 50% leakier, per unit envelope area, than buildings with large footprints. Large-footprint areas tend to have a higher fraction of their total envelope area in the form of their roof, so if roofs are tighter than walls then one would expect the leakiness per unit of envelope area to decrease with footprint size. It is also possible that a substantial leakage path is the joint between walls and roof, which increases only linearly with building footprint, whereas envelope area increases quadratically; this, too, is a possible explanation for the decrease of leakiness per unit envelope area as the footprint increases.
4. For a given building category, taller buildings appear to be slightly tighter than shorter buildings (with single-story buildings being perhaps 10% to 25% leakier than taller buildings, per unit envelope area), but (1) the scarcity of tall buildings in the database lends little statistical power to address this issue, and (2) almost all of the tall buildings are office buildings, so a height effect cannot be distinguished from an effect of building type (item 2). Visual inspection of Figure 7 may suggest that taller buildings are much tighter, but this is largely illusory: there are so many more data points from the single-story category that (in terms of absolute numbers) most of the leaky buildings have a single story.
5. For buildings of a given construction type and activity category, leakiness per unit envelope area is approximately lognormally distributed, with a GSD between about 1.7 and 2.2.

To the extent that a building's activity category is related to building leakiness, this is presumably because the building activity category is a proxy for unknown or unspecified construction methods and design features, rather than due to a causal relationship between activities and leakiness. For instance, the design and construction details of metal-frame strip malls tend to differ from metal-frame office buildings in systematic ways, so it makes sense that metal-frame strip malls tend to have different leakage characteristics than metal-frame office buildings. However, if a strip mall were converted into offices, one would expect its leakage to be similar to that of strip malls, not office buildings. As a result, it cannot be predicted what might occur for combinations of construction methods and building usage categories that are not in this data set. It is not clear that, say, a curtain-wall public assembly building would in fact be particularly tight, even though other curtain-wall buildings appear to be tight, and public buildings tend to be tight, since a curtain-wall public assembly building would probably differ greatly in design from all of the other public assembly buildings and curtain-wall buildings in the project database.

The Commercial Buildings Energy Consumption Survey (CBECS), a Department of Energy data collection effort, characterizes the commercial building stock of the United States in a variety of ways (EIA 2003). As with the definition of "commercial" for purposes of this report, CBECS includes many buildings that are not places of business: its sampling frame includes "all buildings in which at least half of the floorspace is used for a purpose that is not residential, industrial, or agricultural, so they include building types that might not traditionally be considered 'commercial,' such as schools, correctional institutions, and buildings used for religious worship." CBECS data are summarized in Table 3. In the Pacific region, which consists of California, Oregon, and Washington, CBECS reports that 17% of commercial buildings (other than malls) are "educational," as opposed to the 27% in the project database. This report assumes that the mix of buildings in California is similar to that for the Pacific Region as a whole. CBECS was not designed to provide state-by-state estimates of the prevalence commercial building types; although it may be possible to re-analyze the raw CBECS data to obtain statistically valid California-specific data, this project has not attempted to do so.

Table 3. Percentage of all commercial buildings in California, Oregon, and Washington that have a given combination of building usage and wall type. From CBECS (EIA 2003) Pacific Region data.

Percent of non-mall commercial buildings	Masonry	Concrete panel/ tilt-up	Concrete (block or poured)	Siding or shingles	Metal panel	Glass/glass curtain	Other	Total
Education	10	1	1	5	0	0	0	17
Food sales	2	0	0	1	0	0	0	4
Office	11	1	2	5	2	0	0	22
Warehouse/ industrial	2	2	1	1	6	0	0	12
Retail (other than mall)	4	0	1	1	1	0	0	7
Health care	2	0	0	0	1	0	0	3
Public assembly/ worship	7	1	2	2	1	0	0	14
Food service	4	0	1	1	0	0		6
Lodging	1	0	0	1	0	0	0	2
Service	4	0	1	0	5	0	0	11
Total	48	6	11	17	14	1	1	100

Small retail buildings and strip malls are also overrepresented in the project data, accounting for 13% of the project data but only 7% of the buildings in the region. Conversely, service-type buildings (e.g., vehicle services, dry cleaners, gas stations, etc.) are underrepresented in the project database; indeed, it is not clear that any of them are included (although some may be reported as "small retail," so it is hard to be sure). Other types of buildings, including food sales, lodging, warehouses, and health care buildings, are represented in the project database in approximately the same proportions that they occur in the region.

Considering the lack of a sampling plan or indeed any coordination whatsoever between research groups, the overall sample of construction types and building categories is remarkably close to what is found in the Pacific region (California, Oregon, Washington). Recall, however, that the project database contains data from several different *countries*, not just the Pacific coast region that includes California.

Table 3 shows the fraction of buildings in a variety of categories of building usage and wall type. To some extent the percentages in this table can be compared to those in Table 2, although there are some differences: for instance, the CBECS data do not include malls (of which there is one in the project database). More importantly, the project separates "small retail" from "strip mall," but these are combined in the CBECS data. Finally, some of the wall information in CBECS does not exactly match the information in the project database. The project database groups concrete blocks, brick, and stone into a "masonry" category, but CBECS counts brick and stone as one category and concrete in another category that includes both concrete panels and concrete block.

In California, roughly half of the commercial buildings have exterior walls that are built of brick or stone, and a substantial portion of the rest are concrete block. Most of the rest have siding (typically masonry or wood) or shingles that are made with various types of materials as the exterior walls, or are built with metal panels. The classification system used in this project is slightly different from the one used in the 1995 CBECS report due to the limitations of the information published in the original studies. In general, the representations of the various wall types in the project data set are roughly comparable to the CBECS data set: masonry exterior walls are the most common, followed by wood and metal panels, and finally concrete panels and curtain wall.

Application of the Shaw and Tamura model (Shaw and Tamura 1977) can predict air infiltration rates—i.e., leakage rates—if certain parameters are specified: the leakage parameter, the building's height, the indoor-outdoor temperature difference, the wind speed, and the wind angle relative to the building's walls. Chan (2006) has used this approach, assuming leakage parameters are in the range discussed above, using building heights from CBECS, and using annual meteorological data from across the U.S. Results suggest that air infiltration is in the range of 0.1 to 1 air changes per hour for most commercial buildings in the U.S.

3.2.2. Air Exchange Due to Operation of the Heating, Ventilating, and Air Conditioning System

Although air exchange due to the HVAC system is beyond the scope of this study, the following brief discussion is included to provide context for the leakiness results.

The ASHRAE 62 (1999) ventilation standard recommends that outdoor air be delivered at a rate of at least 20 cubic feet per minute per person, or 0.0094 cubic meters per second person, in most indoor environments. Grot and Persily (1986) found that most of the eight office buildings that they measured operated very close to or below the recommended ventilation rate. Measured monthly average ventilation rates ranged from 0.3 to 1.0 air changes per hour (ACH) during the winter months, and were typically well over 1.0 ACH in most buildings in spring and fall. Air change rates tend to be highest in mild weather because many commercial buildings switch automatically (or in some cases manually) into an "economizer mode" in which recirculation of building air is decreased and outdoor air is used to cool the buildings.

Lagus and Grot (1995) measured the total air exchange rates (including both HVAC operation and leakage) of 22 office buildings and 13 retail buildings in California and found the median to be 1.1 and 1.8 ACH, respectively. Assuming a conversion factor of 20 cubic feet per minute per person = 0.8 ACH, Lagus and Grot concluded that the measured ventilation rates are higher than the ASHRAE ventilation rate recommendations, which would be 0.8 ACH for office buildings and 1.2 ACH for retail buildings. The same study also found that schools tend to have higher air exchange rates on average (median = 2.2 ACH), but still not high enough to satisfy the ventilation standard recommended for schools. Among the full set of 49 buildings tested by Lagus and Grot (1995), the typical air exchange rates under normal operating conditions were in the range of 1 to 3 ACH, with a minimum at roughly 0.5 ACH.

Ludwig et al. (2002) reported the ventilation rates of 100 office buildings determined as part of the U.S. EPA Building Assessment Survey and Evaluation (BASE) study. These buildings were randomly selected in 37 cities located in 25 states. The ventilation rates were determined using occupant-generated carbon dioxide as a tracer gas. Ideally, the steady-state carbon dioxide level would be obtained and used to compute the air exchange rate based on mass balance. In practice, however, factors such as the building occupancy level and the fresh-air intake rate of the ventilation system all vary with time. Thus, the indoor CO_2 concentrations measured are also time varying. To overcome these problems, Ludwig et al. chose the 90th percentile carbon dioxide concentration measurement to estimate the air exchange rates. Justification of this choice is detailed in their paper. They found that 80% of the ventilation rates estimated are in the range between 20 and 65 cubic feet per minute per person. Assuming that the same conversion factor of 20 cubic feet per minute per person = 0.8 ACH (Lagus and Grot 1995) also applies here, then the air exchange rate of the 100 BASE buildings ranges from 0.8 to 2.6 ACH.

As would be expected, this evidence indicates that air infiltration rates, which are estimated to range between 0.1 and 1 ACH as discussed in the previous section, are usually much lower than the air exchange rate induced by mechanical ventilation system. In two of the studies in which both the air infiltration rate and the air exchange rate with the HVAC operating were measured in buildings (Cummings et al. 1996; Lagus and Grot 1995), the observed ratios of these two rates were mostly in the range of 0.1 to 0.8. Similar expectations for this ratio are implied by the difference between the range of air infiltration rates estimated by Chan (2006) using the Shaw and Tamura model (1977), which is 0.1 to 1 ACH, and the range of air exchange rates measured in buildings, which is 1 to 3 ACH. The variability in this ratio means that the reduction in the amount of outdoor air brought into the building by turning off the mechanical ventilation systems can be very significant in some buildings, but only modest in others. The amount of fresh outdoor air intake that the mechanical ventilation systems supply also tends to vary seasonally, as discussed previously.

Air infiltration rate predictions yield higher values in the winter because of stronger driving forces. As a result, in winter the amount of outdoor air bought into the building by uncontrolled air infiltration can approach that provided by mechanical ventilation. On the other hand, when the climate is mild and many buildings have their ventilation systems operating at a high rate of outdoor air intake, HVAC dominates uncontrolled leakage as a contributor to overall air exchange.

3.2.3. Apartment Buildings Data Analysis

Compiling, summarizing, and analyzing the available data on apartment leakiness was one of the primary goals of this study, at the same level of importance as analyzing the commercial buildings data. However, the extreme scarcity of apartment data and the complexities of the existing data make it impossible to go beyond the most basic data summaries and analyses. Therefore, the discussion of apartment data is substantially shorter and less detailed than the discussion of the commercial building data.

Data were collected from 14 different studies on apartment buildings in the U.S. and Canada (Wray 2002; Palmiter et al. 1995; Dietz et al. 1985; Lagus and King 1986; Love 1990; Hill 2001; Gulay et al 1993; DePani and Fazio 2001; Shaw et al 1990; Reardon et al. 1987; Kelly et al. 1992; Feustel and Diamond 1996; Diamond 1993; Flanders 1995).

Apartment buildings are, of course, composed of many individual apartments or "suites" that are at least somewhat isolated from each other in terms of air exchange. For this reason, there are several separate issues related to ventilation in apartment buildings.

1. **There is leakage from individual apartments to (or from) the outdoors.** This is important from the standpoint of energy efficiency, since undesired infiltration (or exfiltration) increases heating or cooling costs. Leakage is also important to occupant comfort, since it affects drafts, the presence of moisture problems (which can lead to mold or mildew), indoor temperatures, and the exposure of occupants to outdoor air pollution. This is the primary focus of the portion of the present work that deals with apartments.
2. **There is leakage from one apartment to another.** This is important from the standpoint of occupant satisfaction, since cooking and smoking odors from one apartment can bother occupants of an adjacent apartment. It is also important from the standpoint of occupant health and safety, as occupants are exposed to environmental tobacco smoke and other pollutants from other apartments. This issue falls outside the scope of the present report, which focuses on indoor-outdoor leakage; however, it is clear from the literature review that this is a neglected area of research. Leakage between apartments (and from commercial establishments to apartments, in mixed-use buildings) may lead to a large unintentional exposure of apartment dwellers to potentially hazardous or irritating substances such as tobacco smoke; dry cleaning chemicals or photographic chemicals; cooking gases, particles, or odors; and other pollutants.
3. **There is an interaction between the whole-building leakage and apartment-to-apartment leakage** (i.e., interaction between items 1 and 2 above). If buildings are well compartmentalized (item 1), individual suites or floors can be separately ventilated, but if not, one suite can affect another (e.g., opening a window can change air flows into or

out of every apartment on the floor or even throughout the building). This issue is outside the scope of the present report.

Ten years ago, Diamond et al. (1996) conducted a literature review and analysis of all of the apartment leakage data that were then available. They noted that “the literature on air flow and air leakage measurements in high-rise multifamily buildings is quite limited.” They also said that “what emerges from a review of (the available) studies is the paucity of information characterizing air leakage in multifamily buildings and the typically poor level of control in the provision of ventilation for the building occupants.” The scarcity of data hampered their ability to make quantitative statements concerning the numbers of apartments or apartment buildings for which infiltration is undesirably high. For the present study, the project team had hoped that additional data from the past decade would be sufficient to change this situation, but this was not the case: compared to the data available to Diamond et al., the project found data on only about 30 additional apartments in about 20 additional buildings in all of North America. The same general statements about the lack of data, made by Diamond et al. ten years ago, apply to the situation today.

For apartment buildings, many of the available data concern air change rates rather than leakiness parameters. There are advantages and disadvantages to this. The advantage is that the leakiness parameter is a characteristic of the building alone, independent of the wind, buoyant forces, and other driving forces. That advantage is also a disadvantage, since it means that in order to determine the air exchange rate, a model must be applied that takes into account how the wind speed, indoor-outdoor temperature difference, and building leakage parameters affect the air exchange rate. Since no two buildings act exactly the same, the predicted air exchange rate for any particular building and environmental conditions will often be in error by 30% or more.

The alternative approach of directly determining the air exchange rate—usually by measuring how quickly a tracer gas leaks out of the apartment—has the advantage that it accurately measures the air exchange rate, but it does so only for the specific set of driving forces that are acting at the time of the experiment. If the wind speed and indoor and outdoor temperatures are measured at the time of the experiment, then the air change rate for other environmental conditions can be estimated by using the same sort of error-prone model that must be used in conjunction with leakage measurements. (But at least the model will give the right answer for the conditions that apply during the experiment). Most, but not all, reports of air exchange rates also included wind and temperature information.

Figure 10 shows data on the air exchange rates of individual apartments within 16 different apartment buildings. In 11 of the buildings, only a single apartment was measured. Only two apartment buildings from California (both from Oakland) are included. No other data are from buildings in climates that could be considered similar to the Mediterranean climate of Oakland, California.

Data are quantified in terms of air changes per hour (ACH), which is the volume of the apartment divided by the volume of air that crosses the exterior wall(s) of the apartment in one hour. These measurements were made under ambient wind speed and temperature conditions, and thus are not directly comparable to measurements based on a fixed indoor-outdoor pressure difference. This is a measure of the connection to the outdoors, *not* the total amount of air that enters the apartment from all sources, including other apartments and hallways. Researchers used a variety of methods to attempt to characterize the building with all windows closed, including closing all of the windows (in a University-owned dormitory), asking residents to close windows during testing, and pressurizing adjacent apartments to attain neutral pressure with apartments where testing occurred. The project team did not investigate each researcher's approach, but accepted their results as a measurement of ACH with windows closed.

In winter, warm air in a building tends to rise and escape through the upper levels, to be replaced by air entering from below. (The situation is reversed in summer, if the building is air conditioned). Consequently, researchers have previously noted (Diamond et al. 1996) that heating costs on upper floors of apartments are expected to be less than on lower floors, and this has been observed in the (sparse) data on the subject. Thus, although apartment-to-apartment air movement is not a particularly important factor for the building as a whole—for which the whole-building air exchange rate is the relevant factor—it does have implications for the comfort and health of individual apartment-dwellers. If apartments are billed separately for heating or cooling, apartment-to-apartment air exchange also has cost implications, and may be a cause of nonuniform heating or cooling costs among apartments.

Apartment-to-apartment air exchange also has health and comfort implications, since it means that occupants of one apartment are exposed to pollutants produced in other apartments (Levin 1988). The very small amount of data concerning apartment-to-apartment air exchange suggests that 10%–40% of the air in an apartment comes from another apartment, not from outside (Levin 1988; Palmiter et al. 1995). Even higher values are possible: Dietz et al. (1986) report on a single-family house in which, in certain weather conditions, all (100%) of the air on the topmost level enters from the floor below. Certainly the same phenomenon can occur in multi-unit buildings as well. This issue is outside the scope of this report, which focuses on indoor-outdoor air exchange, but it is an area of research that needs far more attention than it has received and will be revisited briefly in the Conclusions and Recommendations below.

As discussed earlier, air exchange rates (as quantified here in ACH) are controlled not just by characteristics of the building itself, but also by the driving forces of wind, and buoyancy due to indoor-outdoor temperature differences. For multi-story, multi-unit buildings such as apartments, there is no simple relationship between the air change rate (ACH) and building leakage parameters (such as the flow rate at 50 Pa): the relationship depends on details such as the wind direction, the amount of open area that connects different levels of the building, and other such parameters that are not available in the published data.

The reported air change rates in the project database include data from a variety of indoor-outdoor temperature differences, from near 0°C to over 25°C (32°F to 77°F) , with most of the data taken when the indoor-outdoor temperature difference was less than 20°C (68°F). Wind speeds were generally low or moderate, below 1 meter per second for most of the data and below 2.5 meters per second for all of the data.

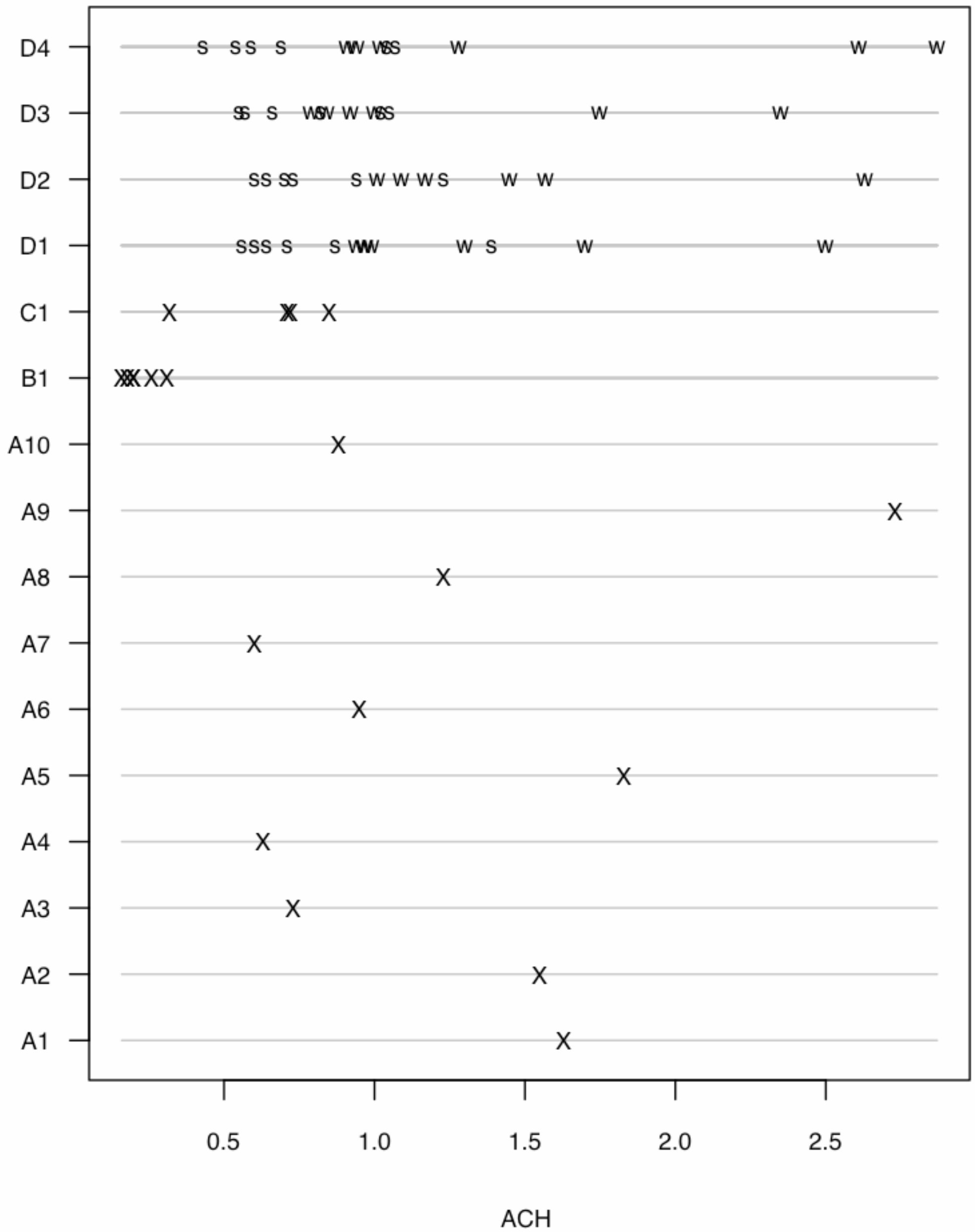

Figure 10. Leakage of individual apartments within 16 different apartment buildings, in air changes per hour (ACH), measured under ambient wind and temperature conditions. The letters “s” and “w” represent summer and winter measurements, respectively, for a study in which the same apartments were measured in both seasons. For the row names, letters A-D indicate different studies, numbers indicate different buildings within each study, and each plotted symbol represents a different apartment within the building.

The observed air change rates, mostly from 0.5 to 2 ACH, are higher than data from single-family houses in weather conditions such as these: typical air exchange rates in houses in these conditions would be of the order of 0.2 to 1 ACH (Pandian et al. 1998; Wilson et al. 1996), or about half what is seen in the apartment data.

Based on the small amount of available data, there is no evidence of large variations in air exchange rate among apartment buildings, with one exception: Building 12 in the project database, (identified as "B1" in the y-axis of Figure 10) built in Portland, Oregon, in 1992 under a special energy efficiency program ("Super Good Cents") and reports lower leakage than do other buildings. The individual apartments within this building have air change rates between 0.2 and 0.4 ACH under moderate wind and temperature conditions, in line with tight single-family homes. Unless windows are opened or additional ventilation is provided in some other way (such as the use of bathroom or kitchen exhaust fans), these apartments, if they were in California, might fail to meet California Energy Code (CEC) requirements: Sherman and McWilliams (2005) report that the CEC requirements correspond to approximately 0.25 air changes per hour.

Discussion so far has addressed data on air infiltration rates under ambient conditions. Figure 11 shows data on leakiness, measured in terms of the flow rate per unit of exterior building envelope, at a 50 Pa indoor-outdoor pressure difference. The median flow rate is 4 $L/(s \cdot m^2)$, the GM is 4.8 $L/(s \cdot m^2)$, and the GSD is 1.7. Given the sparse, nonrepresentative data it is hard to draw any firm conclusions, but these numbers are in line with the observed data from commercial buildings and seem somewhat leakier than typical single-family homes, which have a flow rate distribution at 50 Pa that has a GM = 2.6 $L/(s \cdot m^2)$ and a GSD of 1.6. However, the apartment GM is uncertain by about 10% simply from small-sample variability (see a statistics text such as Spiegel 1992, for example, for the relationship between sample size and statistical uncertainty). The potential for selection bias is far larger than the small-sample uncertainty, so the air infiltration results are only suggestive. The two apartment buildings from California (both from Oakland), are identified as L1 and L2 in the y-axis labels. As stated earlier, no other data are from buildings in climates that could be considered similar to Oakland's Mediterranean climate.

As previously discussed, for apartment buildings there is no straightforward, validated method of predicting air exchange rates from leakiness measurements. Furthermore, the apartments in which air exchange rates were measured are not the same apartments, or even the same buildings, as the ones in which flow at 50 Pa was measured.

The observed apartment indoor-outdoor air exchange rates of 0.5 to 2 ACH are 1.5 to 2 times those of single-family houses, and the observed apartment leakiness values in the range of 3 to 8 $L/(s \cdot m^2)$ are approximately 1.5 to 2 times the values observed in single-family houses. So, apartments seem to be about 1.5 to 2 times as leaky per unit surface area and to have 1.5 to 2 times the infiltration rate as single-family houses, which seems like a consistent story. However, the situation is considerably more complicated than this suggests: the ratio of exterior wall area per unit of interior volume is generally lower for apartments than for single-family houses; the volumes are different, most apartments lack a ceiling (roof) that provides a direct pathway to the outdoors, and there are considerable differences between houses and apartment buildings in terms of the connectivity of interior spaces (e.g., different floors). Therefore, it is by no means obvious that the fact that apartment buildings have double the leakiness per unit of envelope area should imply that they have double the air exchange rate. Given these caveats, and the fact that data are so sparse, the observation that apartment buildings are "twice as leaky as houses and have twice as much air exchange" should be considered preliminary.

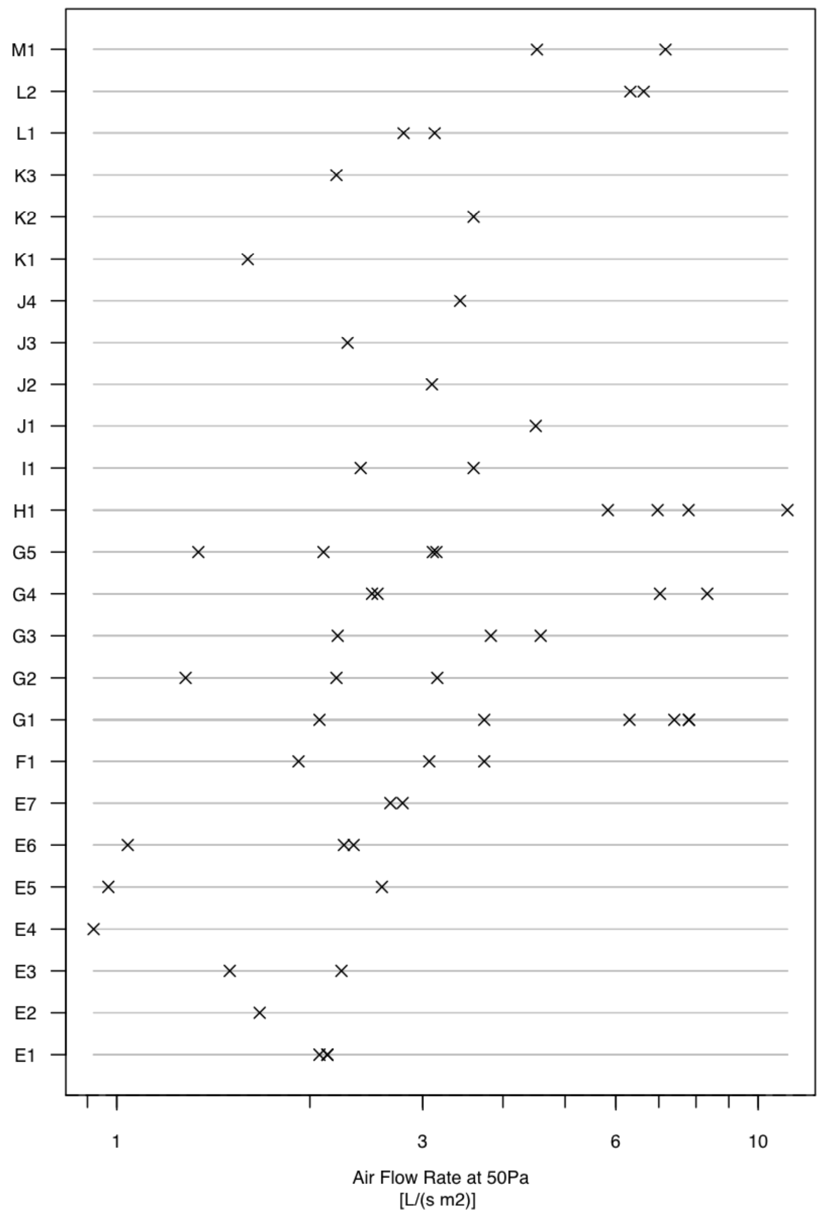

Figure 11. Air flow rate (liters per second, per square meter of building shell) at a 50 Pa indoor-outdoor pressure difference, for apartment buildings. In the y-axis labels, letters E-M indicate different studies, and numbers indicate different buildings within each study. Each X represents a different apartment within the building.

3.2.4. Existing Apartment Stock in California

The American Community Survey (ACS, see Bennefield and Bonnette, 2003, for discussion; 2004 data, discussed in this section, were obtained from U.S. Census website) collects housing data from 244 counties and most large metropolitan areas in the U.S. The ACS does not currently sample every county in California, although the Census Bureau intends to modify the survey to do so in the future. The survey is designed to permit estimates of statewide statistical distributions even though not all counties are included. The 2004 results estimate that there are 12 million occupied housing units in California, and another 800,000 unoccupied units (about 80% of them apartments). Most California housing units (58%) are single-family detached houses, and about 4.5% are mobile homes. The remaining 37.5% of housing units are in multi-unit structures, including duplexes, townhouses or row houses, and apartment buildings.

Table 4. Multi-unit or attached housing in California, by size of building

Type of building	Number of units (thousands)	Percent of all housing units	Percent of non-single-unit detached housing units
1-unit attached	940	7	17
2 units	320	3	6
3 or 4 units	720	6	13
5 to 9 units	820	6	15
10 to 19 units	660	5	12
20 or more units	1402	11	25

Table 4 shows the number of housing units that occur in buildings of different sizes. Excluding single-family detached houses, about half of the remaining housing units are in buildings that contain at least five apartments, and about a quarter are in buildings that contain 20 or more apartments.

There is considerable variation in the housing stock between heavily urbanized areas and less-urban areas. For example, in San Francisco County (which contains San Francisco, California, one of the densest cities in the country) 24% of all housing units are in buildings of 20 units or more, and 45% are in buildings of 5 units or more. In contrast, in Tulare County, a rural county south of Fresno, only 2% of all housing units are in buildings of 20 units or more, and only 6% are in buildings of 5 units or more.

3.3. Gaps in Current Knowledge

The general lack of knowledge about building leakiness, for both commercial buildings and apartments, has been noted by previous researchers (Diamond et al. 1996; Persily 1999). Based on available data, even basic questions such as the following cannot be definitively answered:

1. How many buildings of different types are leaky or extremely leaky?
2. What is the total statewide energy loss attributable to undesired air infiltration?
3. What is the reduction in exposure to airborne pollutants when people shelter indoors from an outdoor airborne hazard, especially in buildings that lack HVAC systems or that are not operating such systems?

There are two ways to look at the coverage of the project's commercial buildings database. On the one hand, comparing the data in the commercial buildings database with data on the overall mix of commercial buildings in the Pacific Region (Table 3), it does not appear that most categories of building are *proportionally* undersampled or oversampled, with three exceptions: (1) service buildings (such as gas stations, car washes, dry cleaners, etc.) are somewhat undersampled, (2) educational buildings are somewhat oversampled, and (3) small retail buildings are somewhat undersampled. On the other hand, in terms of *absolute* numbers, there are very few categories of buildings that are sampled well enough to characterize the distribution of air leakage accurately. Only five building categories in the U.S. have as many as eight measurements, for example. Additional sampling needs are not so much a matter of filling specific gaps, as simply collecting more of everything.

As for apartment data, there is a surprising paucity of information. There is no prospect of comparing, say, new apartment buildings to old ones, or mechanically ventilated ones to naturally ventilated ones, or tall ones to short ones. The available database is extremely deficient.

Another important knowledge gap is outside the scope of this report but noteworthy: What is the statistical distribution of air flow between apartments within an apartment building, or between businesses and apartments in a mixed-use building? Although it was not a focus of this work, the project team encountered publications that discussed this issue, and some of them (Levin 1988; Palmiter et al. 1995) reported that more than 50% of the air entering some apartments came from elsewhere in the building rather than from outdoors. This suggests that apartment dwellers may be exposed to significant amounts of pollution, such as cigarette smoke, dry cleaning or photo developing chemicals, cooking gases and odors, etc., that originates in other units in their building. Lawrence Berkeley National Laboratory researchers Craig Wray and Darryl Dickerhoff identified this issue (in private communication) as one of the largest data gaps related to residential ventilation and air quality.

4.0 Conclusions and Recommendations

4.1. Conclusions

Researchers have previously noted that the existing data on leakiness of commercial buildings and apartments are sparse, are collected using a variety of protocols, and are based on a nonrepresentative sample of buildings. This study's review of the literature and discussions with researchers in the field indicate that those data shortcomings still exist.

4.1.1. Commercial Buildings

The commercial buildings database compiled by this project includes 164 buildings from the United States and 267 buildings in all. Some categories of buildings, such as masonry schools, are fairly well represented, but data for most building categories are extremely sparse or, in some cases, completely missing. Also, the data are not statistically representative, but instead generally represent whatever buildings the researchers were able to access, and were able to find funding to measure. What's more, almost all of the buildings in the database are from outside California. As a result, no definitive conclusions can be reached about the situation in California. However, the data suggest the following with regard to commercial buildings overall:

1. Within a given building activity (education, retail, etc.) there appears to be little systematic variation in leakiness as a function of construction type.
2. Within a given construction type (metal-frame, masonry, etc.) there is some evidence that schools and public assembly buildings tend to be somewhat tighter than average and that warehouses tend to be leakier than average.
3. Buildings with small "footprints" (i.e., small roof area), under 1000 m^2, tend to be 25% to 50% leakier, per unit envelope area, than buildings with large footprints.
4. Taller buildings appear to be slightly tighter than shorter buildings (with single-story buildings being perhaps 10% to 25% leakier than taller buildings, per unit envelope area), but (a) the scarcity of tall buildings in the database affords little statistical power to address this issue, and (b) almost all of the tall buildings are office buildings, so a height effect cannot be distinguished from an effect of building type (item 2).
5. For buildings of a given construction type and activity, footprint size, and height, leakiness per unit envelope area is approximately lognormally distributed, with a geometric standard deviation between about 1.7 and 2.2.
6. On average, commercial buildings may be about twice as leaky as single-family houses, per unit of building envelope area.

4.1.2. Apartment Buildings

Apartment building data are even more deficient than commercial building data, so no detailed analysis was possible. Available data suggest that apartment buildings tend to be about twice as leaky as single-family houses, as quantified by air flow per unit area of building shell when a given indoor-outdoor pressure difference is applied.

This finding suggests that there may be a potential for substantial energy savings by reducing air infiltration rates for apartment buildings. It also suggests that “sheltering” indoors from outdoor pollution (a chemical spill, a terrorist attack, or simply a high-pollution period) may be substantially less effective in apartment buildings than in houses. However, given the data limitations it is very hard to be sure that this is the case.

Data from the U.S. and Canada are consistent with apartment leakage parameters being approximately lognormally distributed, with a geometric standard deviation between 1.5 and 2.5. Almost none of the available data are from California, so it is not known whether California buildings are typical of others in the database. One might speculate that they should be somewhat leakier, since there is less need or incentive to insulate them (because of the generally mild climate in the most populous portions of the state), but there is no direct evidence that this is the case.

Obtaining useful amounts of information about California apartment leakiness would require a substantial experimental program as outlined in Section 4.2.2.

4.2. Recommendations

4.2.1. Further Study of Commercial Buildings

The deficiencies in the available commercial building data could be addressed through an experimental program to measure air exchange rates or leakage parameters in a representative sample of buildings. If such a program is to be undertaken, it should not rely on the usual past practice of using a “convenience sample” of buildings that happen to be available to the researchers or in which the building owner or operator is especially motivated to participate in an experimental program. The use of convenience samples has been very important in the past —indeed, if not for this practice there would be no commercial building measurements at all.

However, any future research program needs to be large enough to make measurements in at least 10 buildings in each category on which it focuses, and those buildings should be selected to be statistically representative of their categories. Ideally, a stratified random sample of the buildings in California would be conducted, with stratification used to ensure that some buildings are sampled even for unusual building categories. Such a program could provide useful, accurate, quantitative data concerning building leakiness.

A much less ambitious program would focus only on specific issues. Rather than simply sampling fewer buildings of each type than would be sampled in an ideal program, a less ambitious program could reduce the scope (in terms of the types of buildings sampled) but still sample at least 10 of each type. For instance, an obvious question of practical interest is whether recently constructed buildings are tighter (and thus, generally more energy efficient) than older buildings; this could be addressed by sampling, say, 15 new medium-sized office buildings and 15 old medium-sized office buildings, using representative samples of each. Whether such a program would be worthwhile, and on what issues it would focus, is a matter for policy-makers.

4.2.2. Possible Program to Characterize Apartment Building Leakiness

There are some obvious targets for a substantial research program. One question of importance is the level of protection offered by apartments against outdoor air pollution episodes or toxic releases. A program that targets apartment buildings in specific locations where these issues are most likely to be important, such as near refineries and chemical plants, could provide important and perhaps even critical information about risks. Another obvious question, as with commercial buildings, is whether construction or design practices are improving with time, for which the same sort of program as that discussed above for commercial buildings could be performed.

Experiments to measure apartment leakage are usually harder to perform than those for commercial buildings, for several reasons: (1) apartment buildings often do not have central air-handling units and thus pressurization or depressurization must rely on equipment provided by the experimenters; (2) the design of apartment buildings, as individual partially isolated units, can introduce complications; and (3) conducting experiments in apartment buildings generally requires cooperation from many individuals who must provide access to their apartment, compared to experiments in commercial buildings which often involve only a small number of tenants (or only one). These complications are probably some of the reasons that so few experiments have been done concerning air leakage in apartments.

To precisely characterize the leakiness of apartment buildings of different types and ages would require measuring leakage parameters in hundreds of apartments, in dozens or hundreds of buildings. Such a program would require many person-years of effort, and would cost millions of dollars. It is possible in principle that such a program could be justified or could even be necessary—if, for instance, some tenants are receiving such inadequate ventilation that their health is at grave risk—but there is no evidence that this is so. On the other hand, so little is known about apartment air leakage that the possibility cannot be ruled out, either. This is particularly true for new buildings: although existing data do not indicate that newer buildings are particularly airtight, Lawrence Berkeley National Laboratory's Richard Diamond (private communication) reports speaking with an apartment builder who have believed that his building would be "too airtight," so he took steps to ensure that its windows cannot be fully closed. It is possible that new construction techniques, or designs and techniques used by some builders, create apartments that provide inadequate outdoor air unless windows are opened or other actions are taken. Some of the apartment buildings discussed in this report (Building B1 in Figure 9 and Buildings E4 and E5 in Figure 11) seem to have apartments that are very airtight.

One possibility to address the dearth of apartment building data is to perform a small experimental program that collects data on of the order of 30 to 50 apartment buildings of various sizes, ages, and construction techniques. Such a program would have three goals:

1. Improve upon protocols for measuring apartment leakiness in different types of apartment buildings.
2. Provide a rough estimate of the statistical distribution of leakiness of apartments in California.

3. Detect large differences in leakiness among common building types or building ages, if such differences exist.

Each of these goals is discussed briefly below.

Develop Standard Protocols for Measuring Apartment Building Leakiness

McWilliams (2002) reviews dozens of published techniques for quantifying air leakage, or leakage parameters, in large buildings. Classes of techniques include single- or multi-gas tracer gas methods (for measuring air exchange rates) and single- or multi-zone pressurization or depressurization methods (for measuring leakage parameters). Each class of techniques includes many variants, some of them developed by researchers trying to cope with features encountered in certain buildings or types of buildings. For example, to measure leakage parameters of the exterior building shell, a common approach is to pressurize (relative to outdoors) a given apartment within a building, and also to pressurize apartments adjacent to the given apartment so that there is no inter-apartment airflow and all flow must escape to the outdoors. Although this works in some buildings, it fails in others because gaps between walls or between floors can provide another pathway for air to escape.

Researchers who have measured leakage parameters in apartments have done so in only a few buildings. Probably no experimenter or experimental team in the world has experience with making measurements in a wide variety of building types. Conducting experiments on 30 to 50 buildings would allow experimenters to gain experience and proficiency, and to develop methods for dealing with problems that arise in various building types.

Estimate the Statistical Distribution of California Apartment Building Leakiness

The apartment building data discussed in the previous section are inadequate to characterize the distribution of apartment leakiness in the country. What's more, they include only a few measurements from buildings in California, and conditions in California might well differ from the rest of the country because California buildings tend to differ in style and construction from those elsewhere in the country, in part because of climate differences.

An experimental investigation that measures leakage parameters in 30 to 50 California apartment buildings, with measurements in 2 to 6 apartments per building, could probably quantify the overall leakiness distribution well enough to address most questions of interest to the California Air Resources Board, the California Energy Commission, and other concerned agencies. For instance, if the air flow rate at 50 pascals is lognormally distributed with a geometric standard deviation (GSD) near 2, then 30 measurements will allow both the geometric mean (GM) and the GSD to be estimated with a standard error of about 15% in principle. In practice, for a realistic sampling strategy, the standard error might be closer to 20% for reasons discussed later.

Detect Large Differences in Leakiness Among Common Building Types

Apartment buildings are extremely variable in both design and construction:

1. Frame materials can be wood, steel, concrete, etc.
2. Facades can be brick, concrete, wood, etc.

3. Windows can be single- or multi-pane.
4. Heating or cooling systems can be central or apartment-by-apartment, or nonexistent.
5. Building sizes range from a few units to dozens of units.
6. Buildings may or may not have connected ceiling plenums or wall spaces.
7. The building may be insulated, uninsulated, or partially insulated.
8. The building may be new, old, or in-between.

Some of these apartment building features are correlated with each other; for instance, larger apartment buildings are more likely to have connected ceiling plenums or wall spaces.

An experimental program that includes several building types and ages could determine whether some types of buildings tend to be much leakier than others. A program that includes only 30 to 50 buildings clearly cannot hope to address this issue for every building type in the state. However, a carefully designed program could answer questions such as whether large buildings tend to be leakier or more airtight than small buildings, and whether new buildings tend to be leakier or more airtight than old buildings.

Sampling Strategy for an Experimental Program

Theoretically, the best way to estimate the relevant statistical distribution of apartment building leakage parameters would be to perform measurements in a simple random sample of apartment buildings in California, weighted by occupancy (so that an apartment building that has more residents would be more likely to be sampled). Such a sampling strategy would be impractical, however, since it would require researchers to traverse much of the state in order to perform the experiments. The resulting travel costs, travel time, and housing costs would be enormous drains on the budget.

A more realistic approach than a simple random sampling scheme would be to use a stratified sampling scheme. This might be rather complicated, but is nevertheless routine, and many groups or consultants, such as the University of California's Survey Research Center, can define a complicated sampling scheme and determine the appropriate statistical weight to assign to each member in the sample.

One possibility would be to select three or four small areas on which to focus. For instance, one county could be selected from urban coastal Northern California counties, one from urban coastal Southern California counties, one from the Central Valley, and one from the remaining counties in the state. A stratified random sampling system could be used to choose the counties, although in practice simply selecting them for convenience would probably yield adequate results. Within each county, researchers would attempt to make measurements in approximately 12 buildings, including at least 3 large new buildings, at least 3 large older buildings, at least 3 small new buildings, and at least 3 small older buildings.

Once the counties are selected, further spatial subdivision is possible if desired, such as selecting (preferably at random) a portion of the county, such as a single town or city, from which a sample of apartment buildings is to be selected. City rental property records can then be consulted to create a list of rental buildings and the number of units in each. Buildings can be selected from this list, and their owners and occupants can be approached to determine willingness to participate, which in this case means (mostly) willingness to provide access. Logistical issues can be rather challenging, as a set of tenants must all be willing to provide access (for blower door installation, for example) at the same time on the same day.

The effect of a stratified rather than simple sampling scheme is always to reduce the "efficiency" of the data: the statistical uncertainty in summary statistics (such as geometric mean and geometric standard deviation) is always larger with a stratified sampling scheme. The loss of efficiency cannot be quantified without detailed information about the sampling scheme, but for a scheme such as that discussed above, the efficiency might be about half that of a simple random scheme. That is, a simple random sample of 20 buildings might yield the same statistical uncertainties as a 40-building sample collected according to the stratified scheme discussed above. However, measurements on a simple random sample of 20 buildings would likely cost far more than twice as much as the 40-building stratified scheme.

The experimental program outlined here would require a substantial investment of both experimenter time and money. Although the actual measurements in a building can probably be performed in a few days, this must follow a substantial planning period for each building, during which the placement of blower doors, flow meters, and pressure sensors must be determined. Some preliminary experiments might have to be performed and analyzed in order to determine whether air leakage into wall, ceiling, or floor cavities is a substantial effect, and the experimental setup might need to be altered to address such issues if they arise. Obtaining permission from building owners and tenants will also be time-consuming, and may not be possible in all cases, in which case additional effort will be required to identify alternative buildings. Overall, the program should assume that preparation, setup, and performance of the experiments will take a total of at least two weeks per building. Adding administrative time, data analysis, and report writing suggests this to more than a two-year project, requiring two full-time researchers plus some additional help to perform experiments in large buildings (when it is necessary to have extra people to help control blower doors and perform various set-up tasks). Including equipment costs, travel, salaries, and overhead, a program such as this might cost in the range of $1.5 million to $2.5 million.

Additional Data That Could Be Collected

The foregoing discussion deals with indoor-outdoor air exchange and air leakage, which is the subject of this report. Another issue that may be even more important, perhaps by a large margin, is the transport of pollutants within an apartment building. There is a great deal of overlap in the literature between indoor-outdoor air exchange and apartment-to-apartment air exchange. As such, although it was not a focus of this report, this project found that transport within a building may potentially lead to very large occupant exposures to pollutants—such as cigarette smoke; cooking fumes, particles, and odors; and spores, bacteria, or viruses—and that data concerning these issues are entirely inadequate. In mixed-use buildings, building occupants may be exposed to dry cleaning chemicals, photo-developing chemicals, and so on. The issue of internal transport of pollutants within apartment buildings and mixed-use buildings merits more attention than it has received and should be a relatively high-priority area of research.

Research in this area can be performed using passive perfluorocarbon tracer gas techniques (Dietz et al. 1985) that are relatively inexpensive and nonintrusive. If the experimental program described above is performed, it would also make sense to perform within-building experiments in the same buildings at the same time. This would probably increase the program cost by less than 20% and would provide a great deal of valuable data.

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6.0 Bibliography

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7.0 Glossary

ACH	Air changes per hour—i.e., the volume of building, divided by the flow rate (volume per hour) of air leaving the building.
Airtightness	Generic term for resistance to indoor-outdoor airflow that a building provides. See leakiness.
Building shell	Exterior walls and roof of a building. All parts of a building through which air can pass to the outdoors.
Building envelope	See building shell.
Building footprint	The total area enclosed by a building's foundation. Normally equal to the building's roof area.
CBECS	Commercial Buildings Energy Consumption Survey, a data collection effort by the Department of Energy
Exfiltration	Phenomenon of air leaving a building through pathways other than a ventilation system.
Flow coefficient	The term C in the equation $Q = C \cdot A \cdot \Delta P^n$ (see Equation 1). This equation relates the air flow rate (Q) to the leakiness of the building (parameterized by C), the area (A) of the building's shell, and the indoor-outdoor pressure difference (ΔP).
GM	Geometric mean
GSD	Geometric standard deviation
HVAC system	Heating, ventilating, and air conditioning system. A mechanical system that provides air, including air from the outdoors.
Infiltration	Phenomenon of air entering a building through pathways other than a ventilation system.
Leakage	Air flow across the building shell. Same as infiltration.
Leakage parameter	Same as flow coefficient
Leakiness	Generic term for the lack of resistance to indoor-outdoor airflow that a building provides. See airtightness.
NIST	National Institute of Standards and Technology
Pascal	Standard unit of pressure, equivalent to 1 newton per square meter.

Appendices

are available at

www.energy.ca.gov/2006publications/CEC-500-2006-111/CEC-500-2006-111-AP.PDF

Appendix A	Air Infiltration Model for Large Buildings
Appendix B	Analysis of Commercial Building Data
Appendix C	Commercial Building Data
Appendix D	Apartment Building Data